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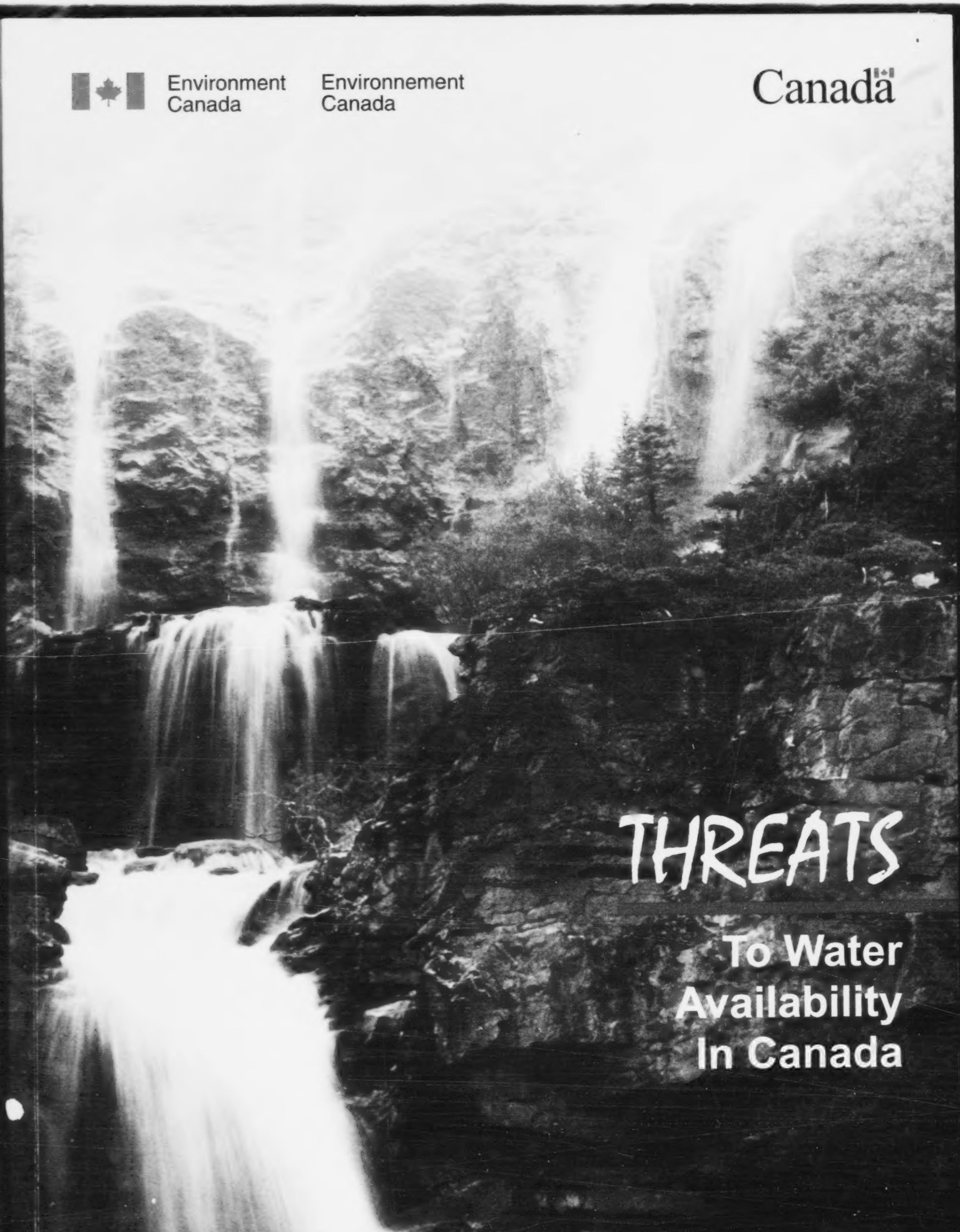

THREATS

To Water Availability In Canada

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THREATS TO WATER AVAILABILITY IN CANADA

NWRI Scientific Assessment Report Series No. 3
and ACSD Science Assessment Series No. 1

NATIONAL WATER RESEARCH INSTITUTE
METEOROLOGICAL SERVICE OF CANADA

Environment Canada
Environnement Canada
Meteorological Service of Canada
Service météorologique du Canada

NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

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National Library of Canada Cataloguing in Publication

Threats to water availability in Canada

(NWRI scientific assessment report series, ISSN 1499-5905; no. 3)

(ACSD science assessment series; no. 1)

Issued also in French under title: Menaces pour la disponibilité de l'eau au Canada.

Includes bibliographical references.

ISBN 0-662-35826-0

Cat. no. En40-237/3-2004E

1. Water-supply--Canada. 2. Water-supply--Environmental aspects--Canada. 3. Water quality management--Canada. 4. Water--Pollution--Canada. I. National Water Research Institute (Canada) II. Meteorological Service of Canada. Atmospheric and Climate Science Directorate III. Series. IV. Series: ACSD science assessment series; no. 1.

TD226.T47 2004 333.91'00971 C2004-900155-8

This report may be cited as follows:

Environment Canada. 2004. Threats to Water Availability in Canada. National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128 p.

Cover photo: Tangle Falls, Banff, Alberta. Copyright: Corel Corporation.

Photo credits: The Steering Committee thanks various Environment Canada staff for use of their photos in this report. Also thanked are Keith Bridger (chapter 1), Hydro-Québec (chapter 2), T.J. Pultz (chapter 4), D.W. Schindler (chapter 8), Chris Hopkinson (chapter 14), and Charles Priddle (chapter 15).

This report is printed with vegetable-based inks and on acid-free, elemental chlorine-free paper containing 50% recycled content including 15% post-consumer waste.

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OVERVIEW

Clean, safe, secure and available water is essential to Canadians. As the Federal Government lead for water, Environment Canada recognizes the importance of strategically addressing water issues of concern to Canadians.

Increased national concerns about water quantity, including recent floods - like the devastating Saguenay and coastal British Columbia floods - droughts, glacier retreat, and the impacts of climate change have prompted this national science assessment, *Threats to Water Availability in Canada*. Production of this peer-reviewed document was directed by leading Environment Canada scientists from the National Water Research Institute (NWRI), Canada's largest freshwater research institution, and the Meteorological Service of Canada (MSC), Canada's leader in weather forecasting and climate science. A companion report, *Threats to Sources of Drinking Water and Aquatic Ecosystem Health in Canada* (http://www.nwri.ca/threats/intro-e.html), detailed the state of science on key water quality issues and was released by NWRI in 2002.

This assessment has been written by experts from academe, industry, and various levels of government, who met in a writing workshop to develop their chapters, and subsequently continued in small writing teams to complete their work. All contributions were reviewed by other respected scientists in the field. The assessment comprises 15 chapters that collectively address a range of threats to water availability: for example, dams, reservoirs and flow regulation; droughts; floods; residential/urban development; industrial/manufacturing demands; mining; climate variability and change; and integrated and cumulative impacts. As in the water quality report, each chapter details current status, trends, and knowledge and program needs.

The section *Threats to Water Availability in Canada – A Perspective*, written by a recognized Canadian authority in water sciences, is provided to give a flavour of each threat, and to identify key issues and findings. Readers are encouraged, however, to examine the particulars within the body of the document for a detailed treatment of issues. In addition, the author of that section has provided his own perspectives on key information gaps and associated recommendations. He has identified four broad areas for action: observational and data needs, critical research priorities, requirements for informed policies and effective management practices, and issues related to leadership.

Ultimately, the report is intended to serve water science decision-makers, resource managers, and the research community as an important reference for developing future research directions and priorities, and sound management policies and practices. The Steering Committee anticipates a lively debate among research, stakeholder and management communities on the issues and needs raised in the document; and looks forward to the timely development of an action plan to address them.

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THREATS TO WATER AVAILABILITY IN CANADA – *A PERSPECTIVE*

Des O'Neill

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Freshwater is a limited resource

With 7% of the earth's land surface, Canada possesses just about 7% of the world's renewable freshwater.

Freshwater is a natural resource, vital to the survival of all living things. In modern societies, it is essential to the functioning of a broad range of economic activities and sectors. Freshwater is a limited resource, however. Although Canada is commonly perceived as particularly fortunate in its plentiful freshwater resources, and Canadian people and industries are among the world's highest per capita users of water, our apparent abundance of freshwater is relative rather than absolute. Our nation's modest population in relation to its immense land area and correspondingly large water resource has much to do with the common perception of unlimited freshwater availability.

A southern population - a northern supply

Second only to Americans in their demands, Canadians use about 1650 cubic metres of freshwater per capita each year...more than double the average European rate.

In fact, many of country's major river systems flow northwards, away from the regions of highest population density, and the increasing concentration of population in urban areas in the south has resulted in a growing mismatch between sources of freshwater and areas of highest demand. The present assessment of threats to freshwater availability in Canada should be seen, therefore, against the backdrop of a limited national resource, not always located in the right place and increasingly under stress from human and other influences.

Water - more valuable than gold?

Caledon, Ontario (pop. 40,000) relies on groundwater as its source of drinking water. The replacement cost of Caledon's drinking water service has been calculated at $33 million annually.

There can be no question that Canada's freshwater supply is an immensely valuable national resource. Recent estimates of water's measurable contribution to the Canadian economy range from $7.5 to $23 billion annually, values comparable to the gross figures for agricultural production and other major economic components. At municipal and sectoral levels, economic valuation is a more readily understandable and meaningful indicator, as illustrated in the case of the Town of Caledon, Ontario.

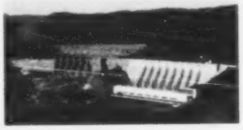
The accessible natural sources of freshwater include rivers, lakes, ponds and reservoirs, groundwater aquifers, snowpacks, glaciers, ice fields and, at the most fundamental level, the liquid and solid precipitation that feeds and replenishes all other sources. In Canada, as in other countries, all freshwater sources are now under noticeable pressure in the face of growing domestic requirements, and other, sometimes conflicting, demands. The needs of municipalities, agriculture and industry, for example, must increasingly be balanced against the necessity of maintaining adequate streamflows in rivers to support important aquatic ecosystems and fish populations. Climatic variability, extreme climatic events, and the spectre of climate change also threaten Canada's sources of freshwater. At the same time, Canadians implicitly assume that governments will protect and sustain their sources of freshwater supply in the face of both population-related demands and natural and human-induced changes in important components of the supply system.

The present report examines individual and collective threats posed to freshwater availability. Based on contributions of participants at a workshop held in Victoria, British Columbia, in September 2002, it synthesizes the collective knowledge, expertise and input of about 100 academic, private sector and government experts in water science and water management. It presents a science-based assessment of the individual and cumulative implications of these stresses, and offers suggestions regarding the role science and policy might play in mitigating their impacts. It draws attention to the need for a more systematic and continuing implementation of established policies and strategies aimed at protection and conservation of water resources. Equally, it emphasizes the need for reinforced and expanded monitoring programs to observe and assess patterns and trends in water demand and use, and relevant environmental and ecosystem parameters. Finally, it examines the cumulative implications of the various pressures and stresses on Canadian freshwater resources and proposes an approach to addressing these threats in a more systematic and integrated manner.

Our current state of scientific knowledge on the hydrologic cycle receives considerable attention in the document, with particular emphasis paid to impacts of human activities, climate variability, and climate change. The worrisome implications of climate change for future access to freshwater in many regions are highlighted, as are the significant changes in important components of the hydrologic cycle that may result from a changing climate. These include changes in precipitation amount, type, geographic and seasonal distribution; in evaporation and evapotranspiration patterns; and in timing and rate of snowmelt. Assessment of the current and foreseeable capacity of climate science to produce useful predictions of future climatic conditions and of the related components of the hydrologic cycle is an important element of the present analysis. A companion publication[1] released earlier addressed threats to sources of drinking water and to the health of aquatic ecosystems in Canada. The threats discussed there are inextricably linked to the threats facing freshwater availability, and, in reviewing this document, it is important to keep in mind that these have direct implications for drinking water supplies and ecosystem health.

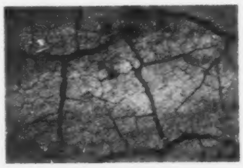
Commencing with a brief overview of the history of water management and use in Canada, **Chapter 1** of the report discusses a broad range of related topics under the heading "Water Allocation, Diversion and Export." These include international and interprovincial apportionment (i.e., the quantitative division of streamflows among jurisdictions), magnitude, impacts and implications of interbasin diversions, the relatively new emphasis on protection of "instream" values, the controversial debate on water exports, and the potential influence of evolving aboriginal rights.

Chapter 2 proceeds to examine dams, reservoirs and flow regulation from the perspective of the threats they may pose to the overall availability of freshwater. The impacts of dams and other impoundments on water quality, chemistry and thermal structure, river ice regimes, sediment load and deposition, and the integrity of aquatic systems are described. Among emerging issues, concerns are identified surrounding dam safety and decommissioning, as is the need to reassess these aspects in light of climate change and its future impacts on hydrologic regimes. Attention is also drawn to the contrasting perceptions of dams as sources of "clean" hydropower and as possibly significant sources of greenhouse gases.



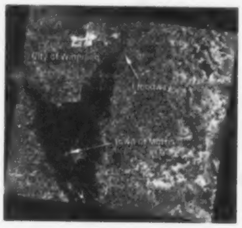
A changing climate may imply more water shortages

Historically most frequent in the southern Prairies, droughts are now a focus of scientific concern that climate change may increase their frequency, duration and severity in all regions of the country. Their causes and impacts, and their present and future implications for freshwater availability are addressed in **Chapter 3**. The current status of and future requirements for drought monitoring, modelling, and prediction are also discussed, as is the potential of drought adaptation strategies.



A changing climate will change flood patterns

At the other end of the hydrologic spectrum, floods and flooding cause major human disruption and exert both positive and negative influences on natural systems. Floods impose direct and indirect pressures on the availability of freshwater by damaging infrastructure, contaminating water supplies, and changing patterns of groundwater recharge. Spring floods, fed by melting snow, are a notable feature of most Canadian rivers and streams. A warming climate may significantly change their timing and magnitude, particularly in southern regions of the country, directly affecting the seasonal and annual cycles of streamflow and freshwater availability. **Chapter 4** of the report examines these and related issues, highlighting needs to reassess estimates of Probable Maximum Flood, to update flood risk zoning maps and other planning approaches, and to apply such tools more consistently in land-use planning.



Urban supplies are already under stress

Urban and residential requirements exert a primary demand on freshwater resources, and urbanization is proceeding at an accelerating pace in Canada. Urban expansion directly affects water availability for other sectors through its impacts on storage and runoff patterns and on water quality. Municipal uses now represent 11% of Canada's total freshwater consumption, with residential requirements contributing about half of that figure. During the 1994 to 1999 period, roughly 26% of Canadian municipalities reported water shortages as a result of increased consumption, drought or infrastructure problems. Notably, municipalities reliant on groundwater reported the most frequent supply difficulties. **Chapter 5** examines the growing stresses placed on water supplies by urban and rural development. It also draws attention to various strategies used to mitigate these pressures, including demand management and increasing emphasis on reuse and utilization of lower quality water sources.

The thermal power generation and manufacturing sectors are Canada's largest and second largest users of water, and the very large demands these activities place on the nation's available supply are reviewed in **Chapter 6**. Factors affecting their future requirements for water are also addressed, emerging issues identified, and related policy, program and research needs highlighted. Among the emerging issues identified are the growing requirements of high-technology "new economy" industries for substantial amounts of high-quality water, possibly from already stressed municipal sources.

Agricultural water consumption tops the scale

Agriculture is Canada's largest net consumer of water, using about 70% of the water it withdraws from rivers, streams, reservoirs, and wells. Consequently, this vital sector exerts major pressures on the available water supply, particularly in the Prairie Provinces where 75% of all agricultural withdrawals occur. **Chapter 7** examines trends in agricultural water usage and issues arising from agricultural water demands. It draws attention to the fact that about 85% of agricultural water use is for irrigation[2] and that climate change is projected to increase this demand. It also points out that improved techniques such as irrigation scheduling and drip irrigation can yield substantial savings in water usage, and urban wastewater also has potential for irrigation of some crops.

Disappearing glaciers - reduced streamflows?

Rocky Mountain glaciers that supply up to 10% of the base flow used for irrigation in western Canada may shrink dramatically during the next century!

Meltwater from Rocky Mountain glaciers is identified as an important contributor to baseflow in many western rivers and streams; consequently, predictions that these glaciers will disappear during the next century raise serious concern from the perspective of agricultural and other demands for water.

Forests are important...

Canada possesses about 418 million hectares of forestland, about 10% of the world's total, and the forest sector is a major contributor to the national economy. Forests play a vital role in the hydrologic cycle, influencing patterns of evapotranspiration, runoff and soil moisture. Disturbances caused by forestry operations and fires, however, exert significant impacts on streamflow, water quality, sediment discharge, and groundwater recharge. **Chapter 8** examines forests and forest practices in relation to the contributions they make and the threats they pose to the nation's water resources. The impacts on the hydrologic cycle of forest fires, insect infestations, and practices such as clear-cutting are reviewed. In addition, the important role played by forests in the global carbon cycle is discussed.

Is oil more valuable than water?

The oil and gas industry in Alberta has the rights to 25% of the province's groundwater supply for use in the recovery of oil from wells.

The Canadian mining and petroleum industries are among the world leaders in resource extraction. While mining places limited and location-specific demands on water supplies, the sector becomes a high-demand user of freshwater when associated refining, smelting and manufacturing operations are considered. Furthermore, the release of substandard water from abandoned mines is a significant threat to freshwater availability in some areas of the country. The petroleum sector, for its part, has large and growing requirements for freshwater. High-demand applications include extraction of oil from tar sands and injection of water into deep formations to enhance hydrocarbon production. The large amounts of wastewater from oilsands production are of poor quality and must be held in containment for long periods, while the injection technique results in permanent loss of water to other uses. **Chapter 9** discusses uses of water by the mining and petroleum sectors, impacts of droughts, floods and climate change on their operations, and challenges faced by the industry in responding to increasing demands for resources in the face of more stringent environmental regulations and climatic variations and extremes.

Groundwater is a hidden and uncertain resource

About 30% of Canadians rely on groundwater... municipal water shortages are most frequently reported by communities supplied from groundwater sources.

Groundwater is, as noted earlier, a vital component of Canada's freshwater resource, supplying a substantial fraction of municipal, agricultural and other requirements for water. As outlined in **Chapter 10**, our knowledge of the groundwater regime is considerably more limited than is the case for surface water[3]; moreover, management of groundwater is often the responsibility of different agencies than those accountable for other water resource components. Consequently, there are both deficiencies in knowledge and institutional issues to be addressed in developing policies and strategies for management of groundwater.

Chapter 11 examines potential impacts of climate variability and climate change on water availability in rivers and streams. It reinforces the fundamental importance of systematic, long-term monitoring of hydrometeorological parameters in representative large and small watersheds in all regions of the country. Concluding sections stress the need for enhanced priority, sharpened focus, clearer leadership, and increased resources in addressing the potentially dramatic impacts of climate change on water availability in streams and rivers.

Canada - a land of lakes

Roughly 14% of the world's lakes larger than 500 km² are located in Canada.

Canada's more than a million lakes cover about 7.6% of its land area and there are, in addition, over 900 major reservoirs. Lakes and reservoirs are vitally important sources of freshwater for municipalities, agriculture, industry, recreation and other activities, as well as being important ecosystems in their own right. **Chapter 12** discusses impacts of climate change and increased consumptive use by humans on lakes and reservoirs. The authors identify and comment on the probable responses of these water bodies to climate variability and climate change, pointing out that there are variations in the sensitivity of individual lakes. They stress that climate scenarios derived from the present generation of climate models give grounds for concern that reductions in lake and reservoir levels may occur in the foreseeable future. Such reductions could result from changes in timing and rate of melt of snowpacks and glaciers, changes in precipitation patterns, and increases in evaporation associated with a warmer climate.

Canada's peatlands may be a climate time bomb!

Canada's peatlands contain about 150 billion tonnes of carbon…about 25 times the amount of fossil fuel carbon released to the atmosphere world-wide each year.

Poorly understood by the public at large, wetlands are vital components of the hydrologic regime, modulating discharge regimes in rivers, recharging groundwater aquifers, and acting as reservoirs in the cycle of production, release, and storage of important greenhouse gases. In addition to being important ecosystems in their own right, they absorb, store and assimilate contaminants and provide many recreational opportunities. Canada's wetlands occupy about 1,300,000 km², an area slightly larger than the province of Ontario. Occurring primarily in the boreal and sub-arctic regions, peatlands are by far the most common type of wetland, representing about 85% of the total. As outlined in **Chapter 13**, the future stability of wetlands in general, and peatlands in particular, is uncertain in the face of a warming climate[4]. This raises the spectre of dramatically increased releases of greenhouse gases to the atmosphere.

Quelques (disappearing?) arpents de neige!

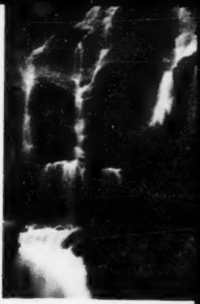
All of Canada is affected by seasonally frozen ground and half of Canada has permanently frozen ground (permafrost).

Described by Voltaire as *"quelques arpents de neige,"* Canada's global image is one of snow and ice through much of the year. In fact, the cryosphere – snow, ice, glaciers, permafrost and frozen ground – is one of the most important components of our physical and biological environment. **Chapter 14** points out that phase changes and seasonal storage involving the cryosphere and cryospheric processes dominate the hydrology of most Canadian river basins. Melt from glaciers in the Western Cordillera, as noted earlier, makes a significant contribution to summer streamflow in rivers and streams. Ice cover exerts important influences on river and lake discharges, as well as on ecosystems, and affects timing and intensity of discharge, evaporation patterns, and local climate. The Intergovernmental Panel on Climate Change has projected that global climate warming will be greatest in arctic and sub-arctic regions. The cryospheric response to a warmer climate may be expected to include a decrease in solid precipitation, a reduction in the duration of snow and ice cover, gradual disappearance of

mountain glaciers, increases in permafrost active layer depth, and melting of ground ice. Such changes will clearly have dramatic consequences for Canada and other high-latitude countries. Quantifying this response and its consequences, however, presents a significant challenge since current climate models are limited in their ability to simulate key characteristics of cold region climates.

Integrated and cumulative threats to freshwater availability are a present reality!

Chapter 15 examines the challenging, but real-world issue presented by integrated and cumulative threats[5] to freshwater availability, and the need to manage these growing and somewhat intractable pressures. The case of the Columbia basin is used to illustrate how independent decisions made in the past by narrowly mandated government agencies contributed to creation of a so-called "meta-problem" extending well beyond the scope of a single agency or level of government. In the face of the complex interrelationships presented by integrated and cumulative threats, the need for more broadly focussed, integrated and consultative water management strategies is stressed. The authors discuss mechanisms established as part of current attempts to address such meta-problems in the Prairie Provinces and the Great Lakes basin (e.g., the Prairie Provinces Water Board and Alberta's South Saskatchewan River Basin Water Management Plan, the Great Lakes Charter).



WHAT TO DO - WHAT IS RECOMMENDED

The individual chapters in this publication draw attention to many sectoral and crosscutting stresses or threats affecting the nation's freshwater resources, and identify where related gaps exist in our current scientific knowledge and understanding. They constitute substantive science assessments by experts in the subject areas addressed in these chapters. In the present writer's view, these science assessments point to needs for urgent and sustained action on a number of fronts to ensure Canadians have future access to adequate supplies of freshwater. The following sections, therefore, represent one individual's synthesis of major conclusions and recommendations from the report along with some thoughts regarding their implications for future policy development and decision making. In overview, these topics can be discussed under four headings:

- **Observational and data needs**
- **Critical research priorities**
- **Requirements for informed policies and effective management**
- **The leadership challenge**

Observational and data needs

To know what to do...you must first know what is happening...

The systematic acquisition of observational data on Canada's freshwater resources represents an expensive and long-term commitment. Well-designed and solidly resourced monitoring programs are, however, absolutely essential to document trends in freshwater supply and use, to support research, and to measure and assess impacts of water policies and management and operational practices.

At the most basic level, the report identifies substantial shortcomings in our knowledge of Canada's freshwater resources, water usage patterns, and water-related infrastructure, pointing out, *inter alia*, that:

- our surface water, groundwater, precipitation, cryospheric and other relevant monitoring networks are inadequately resourced and poorly coordinated. Near-real-time streamflow observations are insufficient to support hydrological modelling applications; observational coverage[6] has key thematic and regional gaps; there are no national groundwater or wetlands monitoring networks; and access to historic data, including paleoclimate and paleoflood records, needs improvement;
- reliable inventories of lakes and reservoirs, aquifer resources, glaciers, the condition and capacity of water distribution and treatment systems, and other important elements such as the number, size and location of mine workings and waste deposits are needed; and
- water demand and usage patterns should be more systematically monitored in sufficient temporal and spatial detail to document sectoral uses, trends and variations, losses, and effects of weather and season. More comprehensive data are also needed on groundwater withdrawals, effluent quality, and ecosystem behaviour in receiving waters.

In summary, authors highlight significant deficiencies in the design, operation and coordination of Canada's surface water, groundwater and climate monitoring networks; in documentation of water demands, usage patterns, effluent quality, and ecosystem impacts; and in basic water resources inventories. Not surprisingly, therefore, they recommend intelligently targeted expansion of baseline monitoring for key components of the hydrologic cycle, representative water demand and usage parameters, and effluent quality and aquatic impacts. In view of this recommendation, it would seem urgent to undertake a coordinated national review of freshwater monitoring programs to identify specific deficiencies and develop prioritized proposals for corrective actions. While considerable rationalization of climate and hydrometric networks[7] has recently been completed, it seems clear that integration and complementarity among various sectoral monitoring programs must be further stressed. Moreover, innovations in monitoring techniques such as satellite remote sensing should be more aggressively and systematically implemented. A valuable supporting initiative might be to develop and regularly disseminate easily understood indicators of the status of freshwater resources[8] and their socio-economic importance, in order to enhance and sustain public awareness of water issues.

Critical research priorities

Scientific investigation enhances our collective capacity for critical insight, informed assessment and rational judgement.

It is widely understood that research is required to generate new knowledge, advance technologies, predict future resource availability and demand patterns, evaluate uncertainties, and assess risks and benefits of policies and strategies. An improved knowledge base is clearly essential for prediction of future threats to the available freshwater resource, and for development of more effective water management policies and practices. In the present context, the implications of climate variability and climate change for water resources and water demand and usage patterns represent over-arching concerns. Clarifying these implications should be a top-priority research challenge. Responding to this challenge requires improved simulations of future climate and more useful seasonal climate forecasts. In particular, authors recommend that:

- the resolution of Global Climate Models (GCMs) be increased, representation of the cryosphere improved, and other appropriate steps taken to enhance their ability to model fields of hydrological importance. In short, Canada's world-class climate modelling capability should receive continuing support;
- the physical causes of past droughts be clarified, and monitoring and modelling of drought conditions improved. Greater advantage should be taken of environmental prediction capabilities to provide early warning of incipient drought conditions, and improved drought adaptation strategies must be sought; and
- the implications of climate variability and climate change for freshwater ecosystems, forest hydrology, permafrost distribution and melting of ground ice, peatlands/wetlands and glaciers be further clarified. A particularly important challenge will also be to factor climate change into flood frequency analysis and flood risk mapping.

On a more general level, authors recommend that research efforts focus on improved understanding and modelling of hydrological processes and systems, including aspects such as effects of land use changes on floods; relationships among land management, soil water balance and partitioning of precipitation; and flow of mine wastes through frozen soils. Greater emphasis should be given to synthesis and integration of research results using models that integrate hydrological and biogeochemical cycles; hydrological process knowledge must be progressively incorporated into watershed models; and up-to-date models applied to flood prediction, building on improving skill in forecasting excessive rainfall events. As supporting activities, improved remote sensing algorithms and statistical testing and diagnostic approaches should continue to be pursued.

Issues related to water quality also need to be addressed: for example, new chemicals of concern and their human and ecosystem health implications; drainage chemistry from mine wastes; and enhanced processes for water treatment, reclamation and recycling. Correspondingly, understanding must be improved of the social and economic factors underlying demands for water or posing impediments to innovation, conservation and recycling, and socio-economic models developed for various water uses and the forces driving demand patterns and recirculation decisions.

Requirements for informed policies and effective management

Scientific understanding provides a foundation for the development of farsighted policies and practices.

Science assessments provide a useful bridge between science and the needs of policy and decision makers.

Implementation of farsighted policies and effective science-based management practices, reinforced by the support of a well-informed public, will be essential to a successful response to the many issues and challenges identified in this report. During the coming decades, the apportionment of water rights on cross-boundary rivers will require much greater attention in view of the growing potential for interjurisdictional conflicts. Optimal institutional frameworks must be sought that facilitate integrated land and water management, while striking a rational balance between competing uses, minimizing long-term threats to freshwater, and ensuring equitable allocation of water within basins and between jurisdictions. Financial approaches should be refined to ensure timely replacement of ageing water infrastructure. Coordination and cooperation among federal, provincial, territorial, municipal and private sector organizations in planning, installing and operating monitoring programs could be enhanced, and linkages between water scientists and water managers further solidified to facilitate application of new knowledge and techniques. Moreover, the concept of sustainable development requires us to consider intergenerational needs for freshwater. In consequence, public understanding and support must be developed through information campaigns that stress the fundamental socio-economic importance of freshwater, the limits to the freshwater resource and the need to conserve and protect it, outlining practical measures individuals and communities can take to that end.

The leadership challenge

Scientific leadership and teamwork are needed to address the many threats to Canadians' future access to freshwater.

At the most fundamental level, this report reinforces the need for strong leadership and an enhanced spirit of interjurisdictional and cross-disciplinary teamwork to address the urgent issues relating to Canada's future access to freshwater. Scientific leadership is clearly required to refine and prioritize requirements and obtain funding to implement needed upgrades to monitoring programs so that Canadians know, with confidence, the extent and condition of their freshwater resources, their socio-economic importance, the dimensions of the threats to them, and the effects of policies, management practices and external influences. Scientific leadership and vision are needed, equally, to target research efforts at issues truly critical to ensuring the nation's future freshwater supply. Furthermore, committed leadership and teamwork over the long term are needed at the highest levels of government to achieve improved coherence in policies and practices within and across jurisdictional boundaries.

CONCLUSION

In conclusion, this report lays out a challenge to develop and implement policies and actions to ensure the sustainability of Canada's freshwater supply in the face of the various threats and pressures outlined in succeeding chapters. Long-term political and institutional commitments will be essential if we are to respond effectively to that challenge. In consequence, the report's fundamental value will be largely measured by the degree to which it captures attention and motivates action by decision makers and institutions. Ultimately, success will have been achieved if the authors' efforts help to ensure Canadians have long-term access, at reasonable cost, to the freshwater needed for human consumption, sustainable social and economic development, and protection and conservation of aesthetic, environmental and other important values.

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[1] Environment Canada. 2001. Threats to Sources of Drinking Water and Aquatic Ecosystem Health in Canada. National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 1. 72 p.

[2] The remaining 15% being used in watering livestock.

[3] Canada does not have a national groundwater monitoring network.

[4] Permafrost degradation is already drastically changing the character of Canadian peatlands as the southern boundary of discontinuous permafrost moves northward.

[5] Integrated threats emerge from combinations of stresses. Cumulative threats and impacts build and are felt over time.

[6] Particularly for the cryosphere, in unregulated basins and in the North.

[7] The establishment of a Reference Hydrometric Basin Network and a Reference Climate Network has resulted from these efforts.

[8] The importance of readily understandable, high impact, snapshots of observed conditions cannot be over stated since requirements for continuing investments in long-term monitoring programs are not well understood by the public at large or by decision makers.

Chapter 1

WATER ALLOCATION, DIVERSION AND EXPORT

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Current Status and Trends

The limited availability of freshwater in Canada at different times and places has led to conflicts among users of this resource, some of which are explored in this chapter. Governments allocate water in ways that influence where, when and how much may be used. Scarcities may be overcome to some extent by reforming the allocation system. Alternatively, water availability may be stretched by means of structures: dams, which hold back flows for release *when* they are more in demand (or less destructive), and interbasin diversions, which redirect flows to *where* they are more in demand. Occasionally, those demands come from outside this country.

Allocation

From the time of first settlement in most of the eastern provinces, the use or allocation of water was governed by the law of *riparian* rights, borrowed from English common law. Only those who owned property adjoining lakes or streams were allowed to use their waters, which they could take for ordinary domestic purposes and other uses, as long as they did not interfere with the rights of other riparians. In the western provinces, however, water laws and institutions evolved differently, primarily because of water scarcity and a concomitant need, from the beginning of agricultural settlement, to convey water beyond riparian land-holdings. Two innovations were introduced, based on experience in Australia and the United States: *prior appropriation*, which refers to licensing of water uses by the Crown on a first-in-time, first-in-right basis to applicants within each western jurisdiction; and *apportionment*, which refers to the negotiated division of transboundary river flows between or among those jurisdictions.

The doctrine of prior appropriation was introduced in British Columbia in 1859 to resolve conflicts over hydraulic mining, and in 1894 in the Prairie region, where federal officials introduced the *North-west Irrigation Act* to provide secure rights to water for irrigation. Each of the Prairie Provinces carried the essential provisions of this Act into its own legislation after being given control of natural resources by the federal government in 1930 (Percy, 1988).

The basic western model entrenches the position of senior water rights at the expense of newer, even if more beneficial, uses of water. Governments have the discretion to reserve unappropriated water in the public interest, but this power has been exercised mostly to make water rights available for large irrigation and hydroelectric projects.

The inherent defects of appropriation law have become clear with the passage of time. It favours early uses, like agriculture, which consume large volumes of water, leaving little or nothing for later, especially urban and instream, uses. Compounding this threat, it hinders the transfer of water licences to other uses or to users who might want to exercise the right at another location. Existing licensees have no incentive to conserve water that could benefit other uses. Some streams have even been licensed beyond what is available in flow. Inevitably, this system has led to regional water shortages, and to engineering investigations to import from more distant unappropriated water sources (Saskatchewan-Nelson Basin Board, 1972). These issues have become especially controversial in southern Alberta where water shortages are common and competition is increasing. Fortunately, reforms are beginning. Amendments to Alberta's *Water Act*, which came into effect in 1999, include provisions for voluntary marketing of water licences within watersheds, subject to a hold-back of up to 10% of the transfer for instream needs (Alberta Environment, 2003).

Like the appropriation doctrine, the quantitative division or apportionment of streamflows among jurisdictions that share a drainage basin is a phenomenon of the dry western environment. Unlike appropriation, it does not appear to constitute a threat to water availability. On the contrary, apportionment agreements bring security to each of the participating governments in terms of a share in the water supply upon which to base their long-term development plans.

The Prairie Provinces participate in formal apportionments of both international and interprovincial rivers (Table 1). For the most part, agreements prescribe an equal, or almost equal, division of water between upstream and downstream jurisdictions. This process began early in the 20th century with the division of St. Mary and Milk flows across the international boundary, and gathered strength after prolonged negotiations over eastward-flowing interprovincial waters, beginning after mid-century. There is some interest in extending formal apportionment arrangements to other Prairie streams that cross the 49th parallel, such as the Poplar, and possibly the Red or its Pembina tributary.

Considering that future changes, among them climate warming and population growth, are bound to press harder on available resources, the interprovincial and international apportionments listed have the advantage of flexibility over most U.S. experience in water sharing, insofar as they are based primarily on percentages of available flow rather than absolute flow entitlements. In all cases, the parties have managed to avoid the protracted disputes that have plagued a number of interstate compacts in the American west (Hundley, 1966).

It remains to be seen whether the process of apportioning western streamflows will spread into other basins or regions, where water shortages are not as severe or widespread. The final hurdle for apportionment is likely to be in the northwest, where the federal, provincial and territorial governments have agreed to principles for managing the waters of the Mackenzie River basin, but bilateral negotiations for most of the seven transboundary crossings are barely underway. They may or may not result in quantitative requirements for flow, its seasonal distribution or its quality.

Two uncertainties remain with respect to provincial appropriation laws and interprovincial apportionment agreements. One is the question of Aboriginal title to water, for which there was provision neither in the *North-west Irrigation Act* in 1894 nor in successor provincial legislation. Some bands are contesting the Crown's establishment of appropriation rights that ignored their

Table 1. Transboundary streamflow apportionments*

a) Canada - United States

Basin	Riparian Governments	Authorization	Formula
St. Mary and Milk rivers, including eastern tributaries of Milk	Alberta, Saskatchewan and Montana	Boundary Waters Treaty, 1909, and IJC Order, 1921	50-50 division of natural flows, with Canada having prior rights on St. Mary, U.S. on Milk
Souris River	Saskatchewan, Manitoba and North Dakota	Water Supply & Flood Control Agreement, 1989	60-40 Sask.-N. Dakota, 50-50 in dry years, with seasonal minimum flow to Manitoba
Poplar River	Saskatchewan and Montana	IJC recommendations 1977, not adopted	50-50 division recommended and followed informally

b) Federal - Provincial - Territorial

Basin	Riparian Governments	Authorization	Formula
Eastward-flowing Prairie rivers	Alberta, Saskatchewan and Manitoba	Master Agreement on Apportionment, 1969	Alta.-Sask. and Sask.-Man. divide natural flows 50-50, with minimum flow requirement for S. Saskatchewan River at Alberta-Saskatchewan border
Mackenzie River	B.C., Alta., Sask., N.W.T. and Yukon	Mackenzie R.B. Transboundary Waters Master Agreement, 1997	Bilateral agreements to be negotiated at 7 boundary crossings. Apportionment?

*Apportionments limited to use of flow for hydropower generation are not included (e.g., Niagara River Diversion Treaty).

Table 2. Canada as hydro country

Region	Dams*		Diversions	
	Storage Capacity 10^9 m^3	% of Capacity for Hydro	Average Annual Flow, m^3/s	% of Flow for Hydro
Atlantic	79	99	740	99
Quebec	423	99	1854	100
Ontario	55	73	576	89
Prairies	113	90	940	92
British Columbia	176	95	340	99
Canada	846	96	4450	97

Sources: Canadian Dam Association (2003), and Day and Quinn (1992) (updated to 2003).
* All large dams with the exception of tailings dams.

non-consumptive riparian uses. Another concern is the legal enforceability of the interprovincial agreement for eastward-flowing Prairie rivers, despite a clause that purports to bind the parties to maintain legislation giving jurisdiction to the Federal Court (Saunders, 1988). If the parties cannot agree on how to interpret any part of the agreement, or if one party simply withdraws its consent to the Federal Court's jurisdiction, there may be consequences of a legal, as well as political, nature.

Interbasin Diversion and Removal

Dams and diversions normally go together: water is stored behind a dam, then withdrawn from its natural course for transfer elsewhere in the same or to another drainage basin. This chapter focusses on interbasin diversions, however, and leaves it to the following chapter to discuss impacts of dams and their reservoirs.

For many years, engineering projects to redistribute river flows in favour of regions experiencing greater demand for water and electricity took the form of diversions of flow through channel modifications, canals, pipelines or similar means. More recently, entrepreneurs have also proposed to move water in bulk by ship and truck tankers, but little activity by this means has been recorded to date. We consider here what is known of impacts of various projects for transporting water. Additional implications raised by the prospect of foreign markets are discussed in the next section.

Nature has provided an environment amenable to surface water manipulation in Canada. More impressive even than the general abundance of fresh surface water is the density of interconnected and almost-connected lakes and rivers that make up our drainage network. These are the legacy of the several advances and retreats of Pleistocene ice fronts, before which meltwaters sought to escape by whatever routes possible, creating and abandoning drainage channels or simply spilling haphazardly from one depression to another. Where nature has shown the way, engineering has not been hesitant to follow, reopening old spillways like that of the Great Lakes from Chicago to the Mississippi River system and of the South Saskatchewan River through the Qu'Appelle Valley. Thus, Canadian diversions have experienced lower costs than those in many other parts of the world through short excavations between proximate water bodies and gravity flows using largely natural channels.

There is no formal inventory of existing interbasin diversions or transfers in Canada. Two criteria have been adopted to qualify diversions:

1. diverted flow does not return to the stream of origin, or to the parent system, within 25 km of the point of withdrawal; and
2. mean annual diversion is not less than a rate of 0.5 cubic metres per second (or a volume of 10,000 cubic decametres).

These have the effect of eliminating localized and smaller withdrawals operated by numerous municipalities, power plants, individual irrigators and trucking firms.

Interbasin diversion projects are found in almost all provinces, and the total flow of water diverted currently between drainage basins is enormous – approximately 4500 cubic metres per second. No other country diverts nearly as much water, or concentrates so much flow for a single function – hydroelectric power generation (Table 2). Of approximately 55 projects identified, the more recent are also the largest – the La Grande (James Bay) program in Quebec, the Churchill-Nelson diversion in Manitoba, and the Churchill Falls project in Labrador, all publicly administered hydroelectric power programs (Day and Quinn, 1992). The national pattern of interbasin diversions has hardly changed in the past decade.

Nechako – Kemano Diversion - A Case Study

The Aluminum Company of Canada (Alcan) entered into an agreement with the British Columbia Government in 1950 to develop a hydroelectric project that would support an aluminum smelting industry and a new population centre in the west-central portion of the province. The project (Phase I) redirects flows of 115 cubic metres per second on average from the Nechako River (Fraser basin) to spill westward by tunnel through the Coast Mountains, a vertical drop 16 times higher than Niagara Falls, into the Kemano River basin. In return for the Company's investment, the province signed over in perpetuity and at a nominal charge a huge area and much of its resource wealth – agricultural and park lands, water, forests and fish. All waters covered by the licence were to be diverted before the year 2000.

There were many trade-offs. In addition to major power generation for Kitimat, the diversion may have reduced the flood threat slightly in the lower Fraser basin, but at the expense of inundating a circular chain of lakes popular with canoeists in Tweedsmuir Park. The upper Nechako River suffered almost 100% loss of flow during the construction of Kenney Dam and filling of its reservoir. After 3 years, 60 to 70% of flow was restored via a spillway that discharged, not from Kenney Dam but down the Cheslatta, a tributary of the Nechako. The comparatively large discharge down this small tributary scoured a deep channel in the unconsolidated sediments and deposited huge volumes of sediment in the upper Nechako (Kellerhals et al., 1979). Due to a smaller dam constructed near the mouth of the Cheslatta, homes and a graveyard of the local Indian community were flooded. The community was forced to relocate on short notice to a new area and unfamiliar way of life (Gomez-Amaral and Day, 1987), which led eventually to demands for redress of their losses.

Beginning in the mid-1970s, Nechako flows were gradually reduced as Alcan increased power generation at its Kemano plant. In 1980, the federal Minister of Fisheries took legal action to force Alcan to release more flows to protect salmon from bed dewatering, siltation and higher temperatures, the Nechako channel being far too wide for the remaining flow. Since then, 30% of prediversion flows have been returned to the Nechako River. Meanwhile, Alcan proposed to take full advantage of its 1950 licence, which gave it rights to divert all the flow from the upper Nechako plus flows from the Nanika tributary of the Skeena River system, thereby increasing the diversion to the Kemano powerhouse from 115 to 202 m^3/s *(Rosenberg et al., 1987). This Kemano Completion (Phase II), after considerable controversy, was rejected by stages, beginning with a 1987 settlement agreement. Alcan, however, remains interested in cost-sharing with the provincial and federal governments and local interests to add a cold-water release from the Kenney Dam, which would improve flows and temperature conditions for Nechako River fish populations, but at the same time allow for increased diversion from the Nechako Reservoir to the Kemano River.*

Flows added to the Kemano River across the drainage divide may have contributed positively to fish resources in that river, if only temporarily and for some species (Fisheries and Oceans Canada, 1984), to hydroelectric production, and more generally to the growth of the regional economy based at Kitimat. At the same time, smelter fluoride emissions in the first two decades of operation were blamed for forest decimation, aquatic habitat damage and workers' health problems locally.

The absence of reliable long-term data on streamflows and ecosystems in both the Fraser and Kemano river basins has made diversion impacts difficult to quantify. Beginning in the late 1980s, a number of committees composed of governments, civil society and Alcan have considered these issues. The Nechako Fish Conservation Program, after 15 years of study, has yet to result in a report on effects of the diversion on salmon populations. A Nechako Sturgeon Recovery Program has not reported on causes for the local decline of this species. The Nechako Watershed Council was formed as part of the Nechako Environmental Enhancement Fund (NEEF), which grew out of the 1997 B.C.-Alcan Agreement to settle legal disputes between the two parties. The Fraser Basin Council (2002) is facilitating work of the Nechako Watershed Council on flow regimes that would be possible with the proposed cold-water release facility at Kenney Dam to meet the interests of a range of stakeholders.

Half a century has passed since this major interbasin diversion project began operation. The absence of benchmark data on all of the affected rivers, however, has frustrated efforts to understand and remediate induced changes. This clearly illustrates the need for careful surveys of both hydrology and other biophysical ecosystem components before significant disturbance is permitted, and for continued monitoring after a project becomes operational.

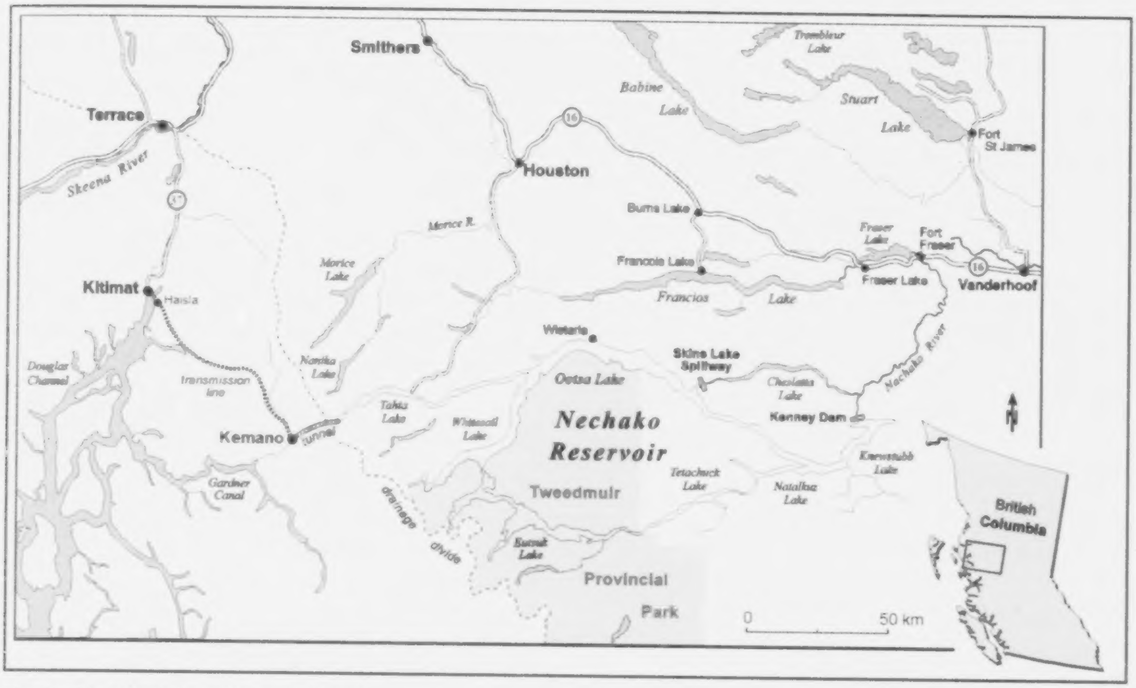

Fig. 1. The Nechako – Kemano diversion.

The benefits of such projects are real and substantial. Just as real, if not as easily quantified, are wide-ranging and long-term biophysical and socio-economic costs. The Nechako-Kemano diversion (Fig. 1) serves as an example.

Beyond the Nechako-Kemano example, other issues related to diversions and other removals of water have been experienced. Unlike dams, which in most cases block fish passage, interbasin diversions risk transferring undesirable fish and associated parasites, bacteria and viruses in the water from one drainage basin or distant source into another basin incapable of resisting them. Concern for protecting the commercial fishery in Lake Winnipeg from alien invasive species like the gizzard shad and rainbow smelt is the main reason Canada and Manitoba insist that the Garrison Diversion in North Dakota, and more recent variations of that project, not divert water from the Missouri into the north-flowing Red River (Kellow and Williamson, 2001). This issue is most threatening in cases of overcoming natural barriers that have existed for thousands of years, such as continental drainage divides (as in the Garrison example) or oceans separating continents. Eurasian sources now account for almost three-quarters of the 160 alien species that have found their way into the Great Lakes, mainly via ship ballast water, and the cost to water intake structures and native species is already in the billions of dollars (Schindler, 2001).

As a country fronting on three oceans, Canada cannot afford to overlook the contribution of freshwater outflows to the marine environment. The flush of spring meltwaters from inland induces upwelling of deep, nutrient-rich salt water into the surface layer, at a time when this is most useful to marine life. Dam and diversion projects are already reducing the natural spring freshet from many rivers, with some evidence of adverse effects in terms of sediment and nutrient losses and reduced fish populations important to coastal ecosystems (Neu, 1982). Aside from its seasonal distribution, how much freshwater might be removed "safely" from a river before it enters the marine environment is a question for which there is no simple answer (Healey, 1992).

Some proposals to divert rivers or remove water by ship or truck transport have been argued on the basis of the small volumes involved as a proportion of the available resources. The other side of the argument, however, is the precedent which even a small removal, such as the proposal by Nova Group in 1998 to remove by ship 60,000 litres per year from Lake Superior, would create for other proponents whose cumulative withdrawals could be much more problematic (Windsor, 1992).

Furthermore, the "surplus" some entrepreneurs see in North America's large lakes is illusory. A prime example is the Great Lakes (International Joint Commission, 2000), where slightly less than 1% of the volume is annually renewable on average, the rest being a legacy of the melting of the Pleistocene ice sheets thousands of years ago.

Water Export

Interbasin diversions of water are widespread in Canada, but none leads south of the border. Likewise, the first ship carrying Canadian water in bulk for sale to any foreign market has yet to leave port. This is not for lack of trying on the part of entrepreneurs who continue to lobby federal and provincial governments for approval of their plans. As for bottled water, its export pales in comparison with the volumes proposed for interbasin diversion or bulk transport of water and has risen only to the level of the export and import of other bottled beverages (Hidell-Eyster International, 1999).

Economic reviews of international water export proposals (Government of Newfoundland and Labrador, 2001; Gouvernment du Québec, 2000; Quinn and Edstrom, 2000) indicate they are not viable at present, in comparison with alternatives such as conservation, improvements in use efficiency, reallocation among users and desalination in regions facing water shortages. In the near- to mid-term, therefore, it is unlikely that Canada will experience any real pressure to export freshwater. In the longer term, however, a potential market such as the American southwest may exhaust some of the more easily applied local alternatives and begin to look more seriously to Canada for relief (United States-Mexico Foundation for Science, 1998). Climate warming, of course, could hasten that eventuality.

Canadian public opinion has been consistently hostile to water export since this issue arose four decades ago. The longstanding concern shared by experts and public alike was that, if the tap were ever turned on to the powerful U.S. market, it might not be possible, as a practical matter, to turn it off. This concern has more recently expanded as a result of international trade negotiations, and the emergence of the North American Free Trade Agreement (NAFTA) in particular, which arguably imposes constraints on a nation's ability to limit water export.

In response to this turn of events and continuing proposals to export water, the Government of Canada (1999) announced a strategy based on environmental rather than trade grounds. In essence, watersheds (drainage basins) would become the geographical basis for preventing bulk water "removals." Mindful of provincial responsibilities over natural resources, the federal government proposed that all senior governments in Canada legislate the prohibition of bulk water removals from watersheds within their jurisdictions. Protecting water, its ecological integrity and its use at the source, within natural rather than political boundaries, was initiated as a defense against bulk removals whether for use elsewhere in Canada or in other countries, thus avoiding the discrimination that could bring international trade challenges.

The abandoned Ogoki Rapids looking northeast toward James Bay from the Waboose Dam. All of the former river flow is diverted south into lakes Nipigon and Superior most of the time.

Despite reservations by some environmental and other interests about this strategy (Gleick et al., 2002), the federal and provincial governments now have laws, regulations or policy in place to prohibit bulk removal of freshwater, and they typically apply to watershed areas within their jurisdictions. Existing interbasin diversions, however, are considered to be "grandfathered" and not subject to reversal.

Some have argued that Canada has a moral obligation to share its water abundance with populations in developing countries and regions who are increasingly unable to provide for their needs. It is the position of the Canadian government that more sustainable alternatives than long-distance importation by ship are available to serve those populations and are preferred by the international aid community, including conservation, recycling, reuse and reallocation of local resources and improved water treatment and distribution systems. Amendments to the federal *International Boundary Waters Treaty Act*, which came into effect in December 2002 primarily to protect Canada's boundary waters from out-of-basin removal, also provide an exception for short-term humanitarian needs.

Knowledge and Program Needs

The state of Canada's freshwater resources under a regime of allocation to users and removal from basins of origin is a legitimate subject for research, even, as limited here, primarily to water quantity concerns. Below we raise some critical research questions.

- On the question of appropriation of water rights by individual and collective users (e.g., irrigation districts), a beginning has been made in Alberta to reform inflexible rules to allow for licences to be marketed from one user to another, whether or not the kind or location of use in the watershed changes. This follows similar reforms of this nature in many states of the American west and in the Murray-Darling basin of Australia. Is this innovation likely to resolve developing conflicts among users in the dry Prairie region of Canada as more water sources become fully appropriated? What kinds of protection should be accorded to instream needs and to other water users and communities which might be affected?

- On the question of apportionment, does the possibility of a province backing out of an existing interprovincial agreement weaken the prospects for similar agreements among governments in the Mackenzie basin or elsewhere? Difficult legal questions remain with respect to the enforceability of these agreements and the substantive legal principles that would apply in the event of an interjurisdictional dispute over water use.
- Apportionment is based on a calculation of natural flow, i.e., the flows that would have occurred in the absence of storage and use. As water consumption approaches the entitlement of an upstream jurisdiction, for example during times of drought, the uncertainties inherent in this calculation become more significant. What new monitoring, data and models will be required to reduce the potential for water conflicts?
- At present, there is no national inventory of existing interbasin diversions. A factual report describing these projects, their history and operation would be a useful starting point toward understanding Canadian experience and concerns about this issue, and is long overdue.
- Improved prediction of morphological change, in both donor and receiving channels, will require continued efforts to monitor and document different kinds of diversions, combined with improved knowledge of river processes and more practical computer models. A comprehensive summary of morphological change via case studies would be a valuable addition to what is known about Canadian diversion projects.
- The question of how much water can be removed from a watershed without compromising its ecological integrity cannot be answered definitively or generally. But research into ecological resilience, risk and uncertainty could prove informative for later, specific, environmental assessments of interbasin diversion or removal proposals.
- River flows have profound effects on physical, chemical and biological processes in coastal waters, effects which may extend for long distances through estuaries and out to sea. Any large-scale project, or series of small projects, to remove regional freshwater resources above the marine zone threatens the stability and productivity of lower trophic levels, fish and mammals downstream. Basic research is required to determine the causes of statistical relationships established in regions like the St. Lawrence River, Estuary, and adjacent coastal waters.
- Guidelines and regulations for ships to exchange ballast water at sea have merely slowed the introduction of species from abroad, a situation that has deteriorated further because of numerous interbasin connections leading foreign invaders into the heart of the continent. The experimental electrical barrier at Chicago is only a first step in trying to prevent species like the Eurasian ruffe from moving beyond the Great Lakes to enter the Mississippi River system and the Asian carp from going in the reverse direction. It is time to revisit the technology and regulation of ballast water exchanges by designing filtration/exclusion systems suitable for ships. In comparison with the costs of control after the fact, it might be feasible for governments to subsidize the industry to put needed innovations into effect.

Acknowledgements

The authors are indebted to Michael Church, Professor of Geography at the University of British Columbia, Vancouver, and Bob Halliday, R. Halliday & Associates, Ltd., Saskatoon, who served as external reviewers and suggested a number of improvements to various parts of the text.

References

Alberta Environment. 2003. Water for life: Alberta's strategy for sustainability. Draft for public discussion. Edmonton, Alberta.

Canadian Dam Association. 2003. Dams in Canada (CD). Edmonton.

Day, J.C. and F. Quinn. 1992. Water diversion and export: learning from Canadian experiences. Department of Geography Publication Series No. 36, University of Waterloo, Waterloo, Ontario.

Fisheries and Oceans Canada. 1984. Toward a fish habitat decision on the Kemano completion project: a discussion paper. Vancouver.

Fraser Basin Council. 2002. Basin news, November. Vancouver.

Gleick, P., G. Wolff, E. Chalecki and R. Reyes. 2002. Globalization and international trade of water, p. 33-56. *In* P. Gleick (ed.), The world's water: the biennial report on freshwater resources 2002-2003. Island Press, Washington, DC.

Gomez-Amaral, J.C. and J.C. Day. 1987. The Kemano diversion: a hindsight assessment, p. 137-152. *In* W. Nicholaichuk and F. Quinn (ed.), Proceedings of the Symposium on Interbasin Transfer of Water: Impacts and Research Needs for Canada. CWRA and NHRC, Saskatoon.

Gouvernment du Québec. 2000. L'eau: ressource à protéger, à pàrtager et à mettre en valeur. Le rapport de la Commission sur la gestion de l'eau au Québec.

Government of Canada. 1999. Strategy launched to prohibit the bulk removal of Canadian water, including water for export. News Release, February 10, Ottawa.

Government of Newfoundland and Labrador. 2001. Export of bulk water from Newfoundland and Labrador.

A Report of the Ministerial Committee Examining the Export of Bulk Water. St. John's.

Healey, M. 1992. The importance of fresh water inflows into coastal ecosystems, p. 255-268. *In* J.E. Windsor (ed.), Water export: should Canada's water be for sale? Proceedings of a Conference held in Vancouver. CWRA.

Hidell-Eyster International. 1999. A perspective on water: The United States and Canada bottled water markets and bottled and bulk water trade. Prepared on contract for the International Joint Commission, Ottawa.

Hundley Jr., N. 1966. Dividing the waters. University of California Press, Los Angeles.

International Joint Commission. 2000. Protection of the waters of the Great Lakes, final report to the governments of Canada and the United States. Ottawa and Washington, DC.

Kellerhals, R., M. Church and L.B. Davies. 1979. Morphological effects of interbasin river diversions. Can. J. Civil Eng. 6(1): 18-31.

Kellow, R.L. and D.A. Williamson. 2001. Transboundary considerations in evaluating interbasin water transfers. Transboundary water transfers. Proceedings of the 2001 Water Management Conference, U.S. Committee on Irrigation and Drainage.

Neu, H. 1982. Man-made storage of water resources: a liability to the ocean environment? Mar. Poll. Bull. 13(2): 44-47.

Percy, D.R. 1988. The framework of water rights legislation in Canada. Canadian Institute of Resources Law, University of Calgary.

Quinn, F. and J. Edstrom. 2000. Great Lakes diversions and other removals. Can. Water Resour. J. 25(2): 125-151.

Rosenberg, D.M., R.A. Bodaly, R.E. Hecky and R.W. Newbury. 1987. The environmental assessment of hydroelectric impoundments and diversions in Canada, p. 71-104. *In* M.C. Healey and R.R. Wallace (ed.), Canadian aquatic resources. Canadian Bulletin of Fisheries and Aquatic Sciences 215, Fisheries and Oceans, Ottawa.

Saskatchewan-Nelson Basin Board. 1972. Water supply for the Saskatchewan-Nelson basin. Report of the SNBB, Canada, Alberta, Saskatchewan and Manitoba. Regina, Sask.

Saunders, J.O. 1988. Interjurisdictional issues in Canadian water management. Canadian Institute of Resources Law, University of Calgary.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sci. 58: 18-29.

United States - Mexico Foundation for Science. 1998. Water and health at the U.S. - Mexico border: science, technology and policy issues. Proceedings of a workshop at Tijuana, Baja California.

Windsor, J.E. (ed.). 1992. Water export: should Canada's water be for sale? Proceedings of a conference in Vancouver, sponsored by the Canadian Water Resources Association.

Chapter 2

DAMS, RESERVOIRS AND FLOW REGULATION

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Current Status

In Canada and throughout the world, dams have been constructed to reduce risks associated with flood hazards, to harness energy for industry and commerce, and to help secure a reliable source of water for domestic, industrial and/or agricultural use. While dams have been integral to agricultural/industrial development, they are also structures that transform river ecosystems over a range of spatial and temporal scales (e.g., Calow and Petts, 1994; Petts, 1984). Of special interest to Canada is the role of cold-regions processes in such transformations (e.g., Prowse and Conly, 1996; Rosenberg et al., 1997).

Through impoundment and increased residency times, dams alter water temperatures and chemistry, which in turn influence rates of biological and chemical processes. Dams create barriers to the upstream-downstream movement of nutrients and organisms, thereby affecting physical and biological exchange processes. They also alter the timing and magnitude of downstream fluxes of water, sediment, and ice, which modify biogeochemical cycles and the resulting structure and function of aquatic and riparian habitat. As dams occasionally collapse, they also present a risk to the built environment and downstream ecology.

Canada's Current Dam Inventory

Although there is no national inventory of all sizes of dams in Canada, the Canadian Dam Association (CDA) periodically conducts an assessment and submits data to the International Commission on Large Dams (ICOLD). In 2000 (Canadian Dam Association, 2003), Canada had 849 large dams (≥10 m in crest height) in operation or under construction. This assessment does not include tailings-pond dams, which would add approximately 84 more dams to the total. The vast majority (70%) of large dams in Canada were constructed solely for hydroelectric production. Of the remainder, 7% were constructed primarily for water supply and 6% for irrigation, mainly in the Prairie Provinces. The rest serve a variety of purposes from flood control to navigation, recreation, or a combination of purposes.

Unfortunately, data concerning volume storage and flooded areas are not catalogued for all large dams. Canada does, however, have ten of the world's largest 40 dams as measured by gross reservoir capacity (ICOLD, 2003). The storage capacity of the 849 largest reservoirs is sufficient to hold the equivalent of two years' runoff from all of Canada, or approximately one quarter the volume of the five Laurentian Great Lakes. Although storage of water in reservoirs increases evaporation, the total effect cannot be estimated because information about reservoir areas and water depths is lacking. Greatest losses occur in shallow reservoirs and where dams have been constructed in hydro-climatic zones characterized by naturally high rates of lake evaporation (den Hartog and Ferguson, 1978), such as Lake Diefenbaker in the central Prairies (e.g., Canada-Saskatchewan, 1991).

No national inventory of small dams exists for Canada but they are estimated to be significantly more numerous than large dams. In British Columbia, for example, there are approximately 2500 small dams (Jolley, pers. comm.), but only 99 are classed as "large" (Canadian Dam Association, 2003). Similarly, Quebec has 5144 dams with heights ≥1 m in their database (Lavallée, pers. comm.) but only 333 large dams (Canadian Dam Association, 2003). Assuming that an average large-to-small dam ratio from these two regions applies to the entire country, Canada has at least 10,000 small to large dams. The effect on storage and evaporation by this larger total is even more difficult to estimate than for the large dams because of the complete lack of data concerning storage capacity and flooded area.

Regulation Effects

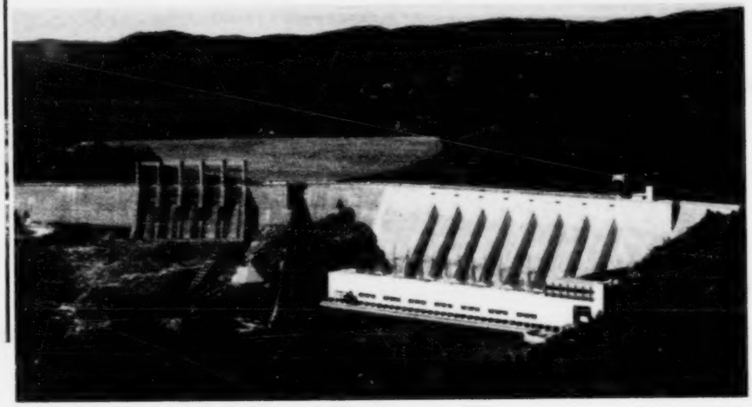
Water Levels and Flow

Two major hydraulic changes generally occur with the construction of a reservoir. First, the water area above the dam will change from lotic (i.e., running water) to lentic (i.e., standing water) in nature, with associated changes in hydrologic and ecological processes. Second, diurnal and seasonal variations in the demand for water or power will cause short- and long-term variations in discharge quite different from those seen in an undammed river.

Typically, the reservoir has two purposes: to increase the hydraulic head or difference in water level across the plant, and to provide storage for periods of low inflow from upstream. Hydroelectric operations are referred to as "run-of-river" when only the first of these is important. Such plants are common additions downstream of large reservoirs (e.g., Peace Canyon Dam below Williston Reservoir) or lakes (e.g., power plants on the Nelson River system, with storage provided by Lake Winnipeg and other natural lakes). They require only sufficient upstream storage to balance flows and to develop the necessary head across the plant.

The ability to store significant amounts of water is a common design feature of larger hydroelectric operations. Demands in Canada are typically at a maximum during winter and at a minimum during summer, a direct contrast to the natural seasonal availability of water over most regions, which is characterized by spring/summer maxima in runoff and winter minima (except in west coastal systems). To counter this imbalance between power demand and the seasonality of the natural hydrologic cycle, a significant portion of the flow is stored during summer and released during winter. Overall, the regulated regime results in a flattening of the annual hydrograph including a dampening of peak flows, particularly where reservoir storage is large relative to runoff volume.

Although the above scenario describes the most common form of seasonal redistribution of flows by regulation, other regime changes can occur depending on the interrelated design of the hydrologic and hydroelectric networks. Some rivers, for example, can experience a decrease in flows throughout the year because a portion of their flow is diverted to feed hydroelectric production in another system. This latter system then experiences an annual increase in discharge, as is the case with the diversion of the Churchill River into the Nelson River in Manitoba, and the Nechako and Kemano river systems in British Columbia (see discussion of flow diversion in Chapter 1).



Manic 2A gravity dam, Quebec, Canada.

On large rivers, the physical and ecological effects of flow regulation can be experienced several hundreds of kilometres downstream, with compounding effects occurring on systems with series of dams. For example, significant, far-reaching, downstream hydrological, biogeochemical, and ecological effects have been observed in the St. Lawrence estuary that have been attributed directly to cumulative effects arising from upstream hydro impoundments (Neu, 1982a,b). Similarly, major environmental concerns have been raised about the compounding effects of multiple dam and causeway construction on a majority of rivers entering the Bay of Fundy (Wells, 1999). By and large, however, quantification of far-reaching cumulative effects (e.g., habitat degradation in estuaries, related offshore nutrient disruptions) has been largely neglected (Rosenberg et al., 1997, 2000).

Ice and Sediment Regimes

River ice is an integral part of most of Canada's rivers, many of which remain ice-covered for six months a year or longer. It also governs a number of processes controlling timing, duration, and magnitude of flow and water levels (Prowse, 1994). Related discharge and water-level hydrographs vary significantly from those of more temperate regions, although the full significance of this to winter aquatic ecology is only now gaining recognition (Prowse, 2001a,b). Any modification of the winter flow regime, as by reservoir regulation, will have concomitant impacts on the ice regime and related winter ecology of a river. These can be highly significant, given that ice is responsible for many of the annual extremes in hydrologic events, such as floods and low flows (e.g., Prowse, 1994).

Regulation can significantly modify duration of an ice cover or even the presence of ice through the release of warm hypolimnetic water. Increased or fluctuating discharge during the winter can lead to changes in integrity of ice cover as well as in location and number of lodgement sites for initial cover development. Moreover, higher flows can lead to covers of greater thickness and rougher surfaces: features that combine to elevate water levels above those occurring under unregulated conditions and greater than those expected under high-flow events. Once an ice cover has been established, regulated-flow conditions can further control its growth and even induce mid-winter breakups and associated flooding.

River regulation can modify the sediment regime of a river through retention of material within the reservoir and through modifications of downstream erosion and deposition processes. Short reservoir life expectancies are associated with small-scale dams that impound rivers with high levels of sediment influx. Continued reduction in storage capacity of such reservoirs through sediment accumulation results in a decreased water-retention capacity, and may lead to an inability to retard the passage of floodwater downstream.

Scouring of a river channel immediately downstream of a reservoir commonly occurs but patterns of morphological change become more complex downstream. Changes in the flow and flood regime have implications relative to the competence of the channel to carry sediment and to the ability of tne system to flush sediment deposited during low-flow events. On large alluvial rivers, degradation processes are constrained to the first few or tens of kilometres downstream of the point of regulation, and a one- to three-metre depth of degradation typically occurs within a decade or two of regulation (Church, 1995).

Further downstream, where tributaries add more material to the river, aggradation may be more common than degradation. Lower regulated flows, especially without the natural freshet peaks, simply do not have the conveyance power to carry material produced by upstream degradation as well as that contributed by the tributary flow. Where aggradation occurs, the nature of the morphological response depends on the character of the alluvial deposits. Typical responses may include lateral scour, channel widening, braiding, and a reduced mean flow depth. Successive species advance of vegetation down the banks onto abandoned floodplains, however, can lead to an adjustment in the overall flow pattern and, ultimately, to a narrower channel.

One critical aspect of changes to a river-sediment regime is time scale. Although some dramatic changes can be observed in the first few years after regulation, the time required for a system to achieve a new equilibrium depends on manner of regulation, form and composition of the channel, and rate at which vegetation becomes established. Because of the huge volumes of sediment involved on large northern rivers and the associated slow rate of vegetation change, the time scale for adjustments can be in the order of centuries. As yet, however, no system in Canada has been studied systematically for more than a few decades (Church, 1995).

Water Quality

Water quality can be significantly affected by impoundment. Physical, biogeochemical, and biological processes occurring within a reservoir can affect the temperature and chemical composition of the water leaving the system to an extent that its quality upon release no longer resembles that of the inflows. The degree to which water quality is affected on a diel, seasonal and/or annual basis depends on factors such as surface to volume ratio and depth of the reservoir; geology and soil geochemistry of the surrounding catchment; latitude of the reservoir; rates and magnitude of sedimentation; magnitude and timing of incoming flows and their residency time; and level of biological productivity in the reservoir.

Temperature changes relate to the reservoir's thermal mass and surface area for radiant exchange, retention time, thermocline development and whether release water originates from the surface or at depth. For instance, in hypolimnetic discharge reservoirs, water is released at depth and is cooler in summer and warmer in winter than unregulated flow at the same location prior to reservoir formation. In contrast, epilimnetic discharge reservoirs (which tend to be shallower) produce elevated downstream water temperatures due to the thermal warming of surface waters. Consequently, these types of alterations in thermal regimes can have profound consequences on the type and complexity of biological communities that can be sustained downstream (Baxter, 1977; Baxter and Glaude, 1980).

Chemical changes in water quality are less predictable due to the complexity of interrelated physical, biological, and chemical processes occurring in the reservoir, both in the open-water season as well as under-ice in the winter. Chemical changes include altered nutrient levels and dynamics, modified water-column and sediment oxygen regimes, nitrogen supersaturation in downstream waters, and increased mobilization of certain metals. In newly formed reservoirs, water quality is often also affected by a trophic upsurge due to release of materials from the newly flooded area, which can be of short duration or last several years in the largest impoundments. One of the more predictable water-quality effects of impoundment is release of mercury from flooded sediments (Rosenberg et al., 1997). Mercury in its methylated form enters the food chain and is bioconcentrated, with highest concentrations occurring in piscivorous fish and birds. These elevated tissue levels can often exceed those recommended for human consumption (particularly in older biota), thereby creating associated human and environmental health risks.

Largely because of the climate-change driven pursuit of "clean" energy sources, attention has also focussed on the role of water storage in affecting production and emission of greenhouse gases (GHG). In contrast to the widespread assumption (e.g., in Intergovernmental Panel on Climate Change scenarios) that GHGs emitted from reservoirs are negligible, measurements made in boreal and tropical regions indicate they can be substantial (St. Louis et al., 2000; World Commission on Dams, 2000). Although Canada is attempting to complete an inventory of the Canadian situation, comprehensive data concerning flooded areas are difficult to access (St. Louis et al., 2000) and accuracy of methods to

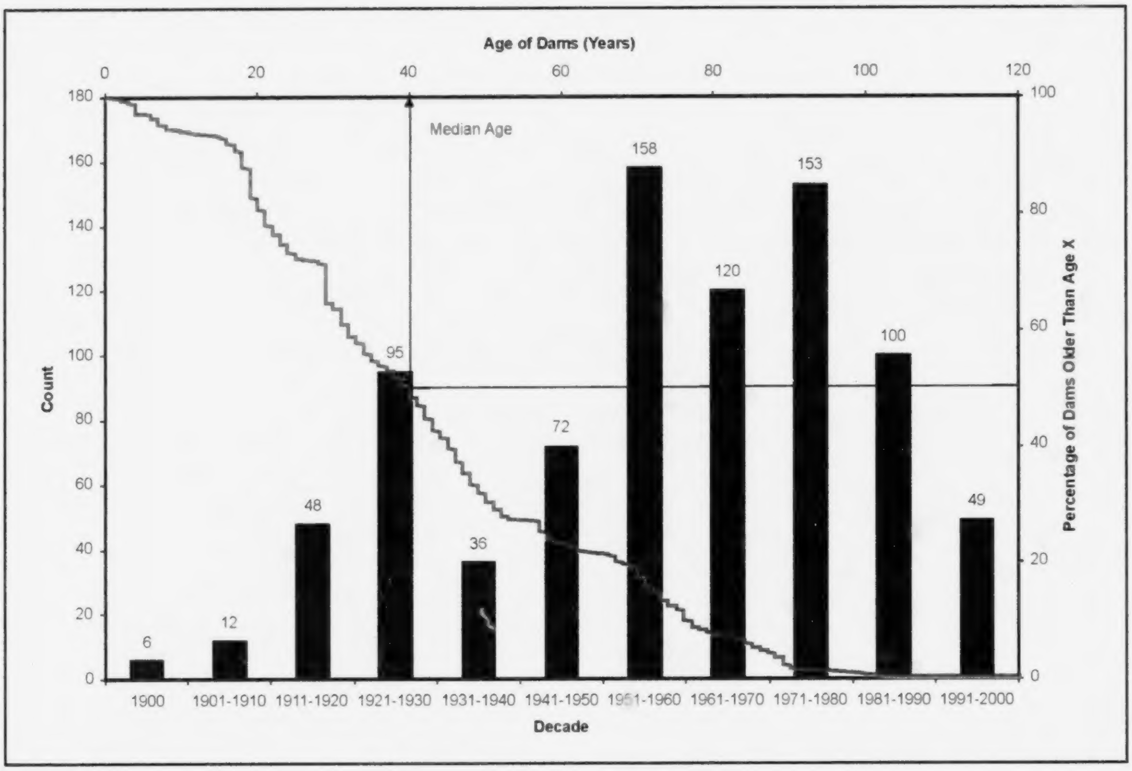


Fig. 1. Number of new Canadian dams constructed by decade (not including tailings-pond dams). Line shows percentage of dams older than x years. Data from Canadian Dam Association (2003).

estimate gas fluxes from reservoir surfaces remains uncertain (Rosa and dos Santos, 2000).

Reservoir and Downstream Ecology

Changes in the physical and chemical characteristics of water from impoundment inevitably affect distribution and abundance of aquatic biota and resulting community structure. Within new reservoirs, fish populations are often quite large during the first few years, largely because of increased nutrients leached from flooded soils and vegetation, enhanced productivity throughout the food chain, and provision of secure sites for spawning and predator protection (e.g., Baxter and Glaude, 1980). Once established, the new physical/chemical characteristics of a reservoir can pose challenges to biota, primarily because they are not in synchrony with natural cycles. Disturbance to spawning resulting from the drawdown/raising of water levels, changes in seasonal temperature cycles, and blocked migration for fish are some major examples. See Baxter and Glaude (1980) and Rosenberg et al. (1997) for more detailed treatment of in-reservoir effects.

Similarly, downstream biota are exposed to a new disturbance regime (e.g., diel and/or seasonal alterations in discharge and thermal regimes), the degree of disturbance depending on the severity of the change and the distance downstream of the dam. For instance, lotic fish species select their preferred habitats by depth, water velocity, and type of substrate. If these change rapidly, as they would immediately downstream from a peaking hydroelectric station, the area would likely be abandoned by these species.

Intuitively, biotic communities should exhibit a dynamic response to opportunities presented by their environment, although the role of physical and biotic factors in structuring aquatic ecosystems is not always clear (Power et al., 1988; Rosenberg et al., 1997). When physical characteristics change too rapidly and in unpredictable frequencies, a stable equilibrium may never be achieved. In general, damaged communities of colonizers, tolerant species and temporary residents established nearest to the dams are replaced by more natural communities downstream as conditions ameliorate and tributaries and groundwater exchanges return the river to a more natural regime (e.g., Ward and Stanford, 1989; Curry et al., 1994).

Dams, designed to meet daily to weekly hydroelectric demands, have more variable water levels and flow regimes than large storage reservoirs. Consequently, they can produce higher disturbance effects on in-channel and riparian processes and related biota (Nilsson et al., 1997; Jansson et al., 2000). Hence, regulated discharges are often directly responsible for reduced habitat diversity and biodiversity in downstream reaches (Jansson, 2002). Although most responses to flow regulation are site-specific, general patterns of large-scale downstream effects are being observed worldwide and a synthesis of these is emerging (e.g., Dynesius and Nilsson, 1994; Nilsson et al., 1997; Rosenberg et al., 1997, 2000).

Trends

Dam Construction

Figure 1 depicts the growth in the number of large dams in Canada from the start of the century to the present. Prior to the 1940s, the majority of large dam construction occurred in southern Ontario and Quebec. Since then, major dam construction has occurred in all provinces and territories. Within the U.S., the most active period of dam building occurred between 1950 and 1970, and has been called "the golden age of dam building" (Doyle et al., 2003). The same comment is frequently made about the situation in Canada. As shown in Fig. 1, however, the 1970s experienced almost equivalent intensity of dam construction as the 1950s. The 1970s peak is primarily due to extensive dam construction in Newfoundland and northern Quebec. Since the 1970s, construction has steadily decreased with the vast majority of development (i.e., >70%) continuing in Quebec. However, given the number of large dams currently under construction and proposals for further expansion, for example, in northern Quebec (Holzinger, 1998; Hydro-Québec, 2002), Manitoba (Lett and Samyn, 2003) and the Northwest Territories (Howatt, 2001), it is truly debatable whether Canada has yet passed its major period of large dam building.

Although northern rivers hold the most remaining potential for large-scale hydroelectric development in Canada, there is also a trend toward construction of small-scale hydroelectric facilities. Numerous small-scale plants were in operation earlier this century, but there followed a gradual move by public utilities to larger generating units to achieve economies of scale. In fact, many small-scale plants were decommissioned following World War II because they became progressively less economical to maintain and operate. More recently, however, because of the size, cost and negative environmental impacts of large dam projects, hydro development has been increasingly focussed on small-scale projects, i.e., those with less than 10 MW of generating capacity. Many of these are run-of-the-river projects. There are currently more than 300 plants in Canada with a capacity of 15 MW or less (Industry Canada, 2003) and numerous others under consideration, particularly for remote communities that rely on high-cost diesel generation. Approximately 5500 sites in Canada are technically feasible for small-scale hydroelectric production (Natural Resources Canada, 2000).

Dam Safety

Of all civil engineering works, dam failure poses some of the highest potential risk of damage to life and property. Moreover, it can lead to loss of drinking and irrigation water supplies, and of hydroelectric generating capacity. Although there is no historical cataloguing of dam failures in Canada, fortunately there has been no major dam failure resulting in loss of life (Bechai and Christl, 2001). There have been, however, numerous incidents involving smaller impounding structures, often designed to mitigate floods of short return period (Watt, 1989). Moreover, as noted by the International Joint Commission with respect to the safety of transboundary dams, concern has been expressed about the lack of a federal dam safety program and regular government inspections. They further point out that although current guidelines developed by the Canadian Dam Association are influential with dam owners and governments, they are only voluntary and fall short of being actual standards or specifications (Legault et al., 1998). In general, three types of initiating events are considered in failure initiation: static, seismic and hydrologic – overtopping by extreme events being the major failure concern. The most significant overtopping event in Canada was associated with the enormous 1996 Saguenay flood (Bechai and Christl, 2001). To avoid flood-generated dam failures, most dam safety studies begin with a hydrologic analysis to derive an Inflow Design Flood (IDF: volume, peak, duration, shape and timing), commonly defined as the most severe inflow flood for which a dam and its associated facilities are designed. For major dams or for those whose failure may cause significant economic losses or loss of life, the IDF is often defined as the Probable Maximum Flood (PMF) (Zielinski, 2001). Unfortunately, in most situations, available data are insufficient to define precisely the probability of large floods and estimates. Hence, estimates must be made beyond the temporal range of the existing data.

Static failure modes of particular concern include erosion, increased seepage, ice effects and, more recently, terrorism (e.g., Martin, 2001). Ice effects are of particular importance to a cold country like Canada, including how changing water levels influence ice loads (Comfort et al., 2000). Seismic impacts on dams can be a concern and some older small structures have been removed because they do not meet current engineering standards. Dam construction is also known to induce seismic activity, water depth being the most important determining factor. One well-established instance of induced seismicity (shock magnitude of 4.3) occurred during the filling of the Manicougan 3 Reservoir in 1975 (Baxter and Glaude, 1980).

The general ageing of dams is another major safety concern. This is especially true for regions where development in the watershed and urbanization below dams have increased the risk to loss of life and property damage. Figure 1 shows the median age of large dams in Canada, which currently stands at 40 years. Based on extensive U.S. experience, the life span of typically unmaintained dams is conservatively estimated at 75 years, refuting the common misconception that the average life of a dam is 50 years (Donnelly et al., 2002). Almost 80% of dam removals in the U.S. have occurred because of concern for dam safety or spillway capacity, but there is an emerging trend toward removal for environmental concerns, as discussed below regarding Canada.

Downstream Biotic Impacts

Over the past three decades, a significant scientific effort has been invested in improving the predictive understanding of relationships between streamflow and aquatic habitat quantity and quality. Collectively these approaches have been referred to as Instream Flow Needs or Requirements (IFN or IFR) (Bovee et al., 1998; Stalnaker et al., 1995). In the 1970s, instream flow determination focussed primarily on methods that attempted to predict: "what is the minimum flow which must be released from the dam in order for the downstream aquatic ecosystem to survive?" Approaches often focussed on maximizing microhabitat for a single life stage of a high-profile fish species (most often salmonids) at a few isolated locations in a river system.

These methods were generally developed for use in small stream and river systems assuming that if flow needs were met, the rest of the aquatic ecosystem would be protected. Examples include the Tennant or "Montana" method (Tennant, 1976) and the Minimum Ecological Flow approach (Stalnaker et al., 1995). Further advancements led to development of the Instream Flow Incremental Methodology (IFIM) and related physical habitat simulation modelling (PHABSIM), which provide more rigorous methods of quantifying effects of stream flow on fish habitat.

Applying these approaches requires detailed knowledge of habitat selected by target fish to be protected – usually a valued game fish. By collecting data on the depth, nose water velocity, and substrate where target fish occur, habitat preference and suitability relationships are generated. Coupled hydraulic modelling is then used to produce detailed maps of the stream showing depths, velocities and substrate, and to calculate species-specific usable habitat area. By simulating different discharges, the model predicts the numbers of target species likely to be present in the area modelled and, by extrapolation, the numbers of fish in a longer reach of river.

IFIM has been widely applied as a tool for predicting potential aquatic habitat effects of water abstraction and flow regulation, in spite of increasing criticisms (see Armour and Taylor, 1991; Bovee et al., 1998; Mathur et al., 1985 for a full discussion). Although IFIM approaches are complex and their results must be interpreted with caution, the method continues to evolve as a more refined decision-support system/framework to examine possible benefits/impacts of flow regulation on various components of the aquatic ecosystem and related socio-economic issues (Bovee et al., 1998; Stalnaker et al., 1995; Walder, 1996).

To develop techniques that can be applied on very large Canadian rivers, recent attempts have been made to use remote-sensing based evaluations of habitat under changing flow regimes (e.g., Courtney et al., 1996), and to broaden the scope of assessments to include all aquatic biota and hydrograph components (e.g., Milburn et al., 1999). Such techniques remain in developmental stages but are much needed since most large dams affect the larger river systems. A recent review of the state-of-the-art in aquatic habitat modelling and conservation flows is provided by St. Hilaire and Leclerc (2003).

Emerging Issues

Decommissioning/Removal of Dams

With changing societal needs in developed watersheds and a growing recognition that dams impair the structure and function of river ecosystems, interest has increased in removal and decommissioning of dams (Babbit, 2002; Poff and Hart, 2002; Pohl, 2002). Typically, dams have been removed because the cost of rehabilitation measures to satisfy dam safety concerns is considered to be higher than the value offered by continued operation of the structure, not because of a dam failure (Donnelly et al., 2002).

There is, however, a great deal of social, economic, and scientific uncertainty about the short-, medium- and long-term environmental benefits of dam removal. While it is known that dams alter the geomorphic and hydrologic processes of riverine systems, our current scientific understanding of how their removal directly affects the downstream flow of water, patterns of sediment movement, and overall channel morphology is limited (e.g., Zhou and Donnelly, 2002a). This is further complicated by ever increasing rural and urban development on downstream floodplains that produce additional constraints on dam removal.

Sediments accumulate behind dams during their operations and the potential for accumulated sediments to have elevated levels of specific chemical contaminants (e.g., metals, petroleum hydrocarbons, pesticides) is high (e.g., Warren and Zimmerman, 1993). Little is known about how the concentrations, fate and distribution of contaminants in the sediments will change with dam removal and affect downstream biological communities, both spatially and temporally. Equally, dams usually alter the residence times of water, thereby affecting various chemical properties. However, uncertainty remains as to how and to what extent removal restores riverine biogeochemical processes to states similar to those before dam construction. As physical barriers, dams often break "natural" food web linkages and interactions that exist between species in riverine communities (e.g., species are not allowed to move freely upstream/downstream). The effects of dam removal on recovery of biological communities have not been well studied.

Climate Change

As noted by the World Commission on Dams (2000), it is generally agreed that the future can no longer be assumed to be the same as the past with respect to design and maintenance of dams. It is becoming increasingly recognized that climate change is likely to have significant impact on the safety of existing dams that were designed based on past records. Although some detailed evaluations of the effects of continuing present-day trends in hydrologic conditions on future IDFs have already been made (e.g., Zhou and Donnelly, 2002b), predictions based on future climate scenarios modelled by GCMs (Global Climate Models) are, for the most part, yet to be conducted. Most future flood predictions are fairly nebulous and rely on generalized predictions about future precipitation and runoff conditions, such as the likelihood of advanced spring melt or shifts from nival (snowmelt dominated) to pluvial (rainfall) regimes (IPCC, 2001). This is understandable given the difficulty of using current GCMs to provide good regional estimates of precipitation. As the quality of such predictions increase and as more detailed RCMs (Regional Climate Models) are developed, it will be possible to conduct regionally focussed assessments of the effects of climate change on specific flood characteristics – information that subsequently should be incorporated into dam-safety assessments.

Knowledge and Program Needs

Overall, the water-quantity related threats associated with dams, reservoirs, and flow regulation fall into three broad categories:

- threats to the aquatic environment created by the installation of such systems
- emerging related threats linked to their removal, and
- the threat posed by climate variability and change.

Although new knowledge is required to address all these threats, Canada first needs to undertake a major program to quantify the degree to which hydrologic systems are impounded and regulated. This would provide, for example, a basis for assessing the cumulative impact of flow regulation on freshwater ecosystems, evaluating future impacts of climate change, and quantifying greenhouse-gas emissions. Canada needs a broader inventory of dams and impoundments beyond the large-dam summary compiled by CDA or Dynesius and Nilsson (1994). Many provinces also inventory small-scale developments and these need to be integrated with the CDA inventory. Furthermore, all such inventories should include data on reservoir surface area, a critical variable for many scientific assessments. Such a variable would permit, for instance, calculation of water losses due to enhanced reservoir evaporation and its significance relative to other water-balance components – information critical for proper planning and managing of basin water resources.

So that the relative GHG merits of different energy-producing sectors can be evaluated, Canada needs to complete an inventory of GHG emissions from Canadian reservoirs. Specifically, net GHG emissions should be calculated for pre- and post-flooding conditions. Given the paucity of such data, calculations will probably have to be based on emissions from flooded and unflooded areas of similar landscapes, and related estimates of the carbon budget for the respective contributing watersheds.

Through its strong effect on the hydrologic cycle, climate change poses a threat to the current network of dams and reservoirs. To minimize risk, more research is required to define new IDFs that can be used to gauge the safety of existing structures and to guide future constructions. There is a related need to quantify the new downstream flow and ice regimes under which dams will have to be operated to minimize downstream flood risks and disruptions to aquatic ecosystems. The potential effects on dam safety posed by climate change also raises further questions about the often-cited need to introduce a more formalized dam-safety inspection program.

Although effects of impoundment on stored water and related aquatic habitats are relatively well studied, significant gaps remain in our understanding of downstream effects. For small systems, there is a dearth of data to satisfy complex IFN-style approaches for evaluating biotic impacts. Moreover, evaluation of regulated-flow impacts on medium to large rivers is in a rudimentary state of development. Since such knowledge is crucial to designing proper flow-management strategies for regulated rivers, IFN advancements need to be made. One logical course of action is refinement of remote-sensing techniques, particularly to quantification of critical habitat. Developing such tools would be particularly beneficial for evaluating near-shore and/or shallow-habitat zones, where productivity tends to be highest and most susceptible to changes in flow.

Since effects of flow regulation have not been systematically studied for more than a few decades, a program to continue long-term assessments of such changes on Canadian rivers is needed. Moreover, to evaluate the range of flow-regulation sensitivity such a program should include sites located in different hydro-morphological regimes. Similarly, effects of flow regulations on downstream ice conditions have received limited study and only in selected hydro-climatic regimes. This should be a special focus for Canada considering most rivers are ice-covered for a significant portion of the year, and ice is a major source of extreme events (low flows and floods) and a significant modifier of hydro-ecological processes. Such a program should also focus on assessing far-downstream effects and cumulative impacts on systems containing multiple dams/reservoirs.

Given the age and shift in requirements for dams/reservoirs in Canada, it is likely that dam removal will become increasingly popular – following a trend already established in other countries, particularly the United States, where attempts are in progress to integrate it into policy and decision making (e.g., The Aspen Institute, 2002). To be better positioned to evaluate costs and benefits of removing dams, it is essential for Canadian science to develop a comprehensive understanding of dam-removal methods and effects applicable to this country's broad range of regulated rivers.

Acknowledgements

The authors are indebted to Ms. Chloe Faught and Mr. Laurent de Rham who tirelessly pursued much of the background data and information employed in this report. Thanks are also due to the various agencies and their representatives that supplied additional up-to-date information about their activities and/or data catalogues. Reviews and comments provided by A.T. Bielak, J.J. Gibson, M. Healey, R. Kallio and D.M. Rosenberg are also gratefully acknowledged.

References

Armour, C.L. and J.G. Taylor. 1991. Evaluation of the instream flow incremental methodology by U.S. Fish and Wildlife Service Users. Fisheries 16: 36-42.

Babbit, B. 2002. What goes up, may come down. BioScience 52(8): 656-658.

Baxter, R.M. 1977. Environmental effects of dams and impoundments. Ann. Rev. Ecol. Syst. 8: 255-283.

Baxter, R.M. and P. Glaude. 1980. Environmental effects of dams and impoundments in Canada: experience and prospects. Can. Bull. Fish. Aquat. Sci. 250. 34 p.

Bechai, M. and L. Christl. 2001. Toward development of a comprehensive dam safety program in Ontario, p. 275-279. *In* Proceedings, Canadian Dam Association Annual Conference, 30 September - 4 October 2001, Fredericton, N.B.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor and J. Henricksen. 1998. Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey, Biological Resources Division Information and Technology Report, USGS/BRD-1998-004. viii. 131 p.

Calow, P. and G. Petts (ed.). 1994. The rivers handbook. Hydrological and ecological principles. Blackwell Scientific Publications, London. 526 p.

Canada-Saskatchewan. 1991. Canada-Saskatchewan South Saskatchewan River Basin Study. Canada-Saskatchewan South Saskatchewan Basin Study Board, Final Report. 87 p.

Canadian Dam Association. 2003. Canadian dam register, March, 2003.

Church, M. 1995. Geomorphic response to river flow regulation: case studies and time-scales. Regul. Rivers Res. Manage. 11: 3-22.

Comfort, G., Y. Gong and S. Singh. 2000. Static ice loads for dam safety analysis, p. 8-17. *In* Proceedings, Canadian Dam Association 2000 Annual Conference, Regina, Saskatchewan.

Courtney, R.F., C. Wrightson and G. Farrington. 1996. A pilot study of the use of remote sensing to analyze fish habitat on the Peace River, July to October 1994. Northern Rivers Basin Study Study Report No. 81, Alberta Environment, Edmonton, Canada.

Curry, R.A., J. Gehrels, D.L.G. Noakes and R. Swainson. 1994. Effects of river flow fluctuations on groundwater discharge through brook trout, *Salvelinus fontinalis*, spawning and incubation habitats. Hydrobiol. 277: 121-134.

den Hartog, G. and H.L. Ferguson. 1978. Mean annual lake evaporation. Plate 17, Hydrological Atlas of Canada, Department of Fisheries and Environment, Ottawa.

Donnelly, C.R., N. Nalder, N. Paroschy and M. Philips. 2002. Issues and controversies associated with dam removals. Canadian Dam Association Bulletin 13(1): 7-18.

Doyle, M.W., E.H. Stanley, J.M. Harbor and G.S. Grant. 2003. Dam removal in the United States: emerging needs for science and policy. EOS, Transactions, American Geophysical Union 84(4): 29, 32-33.

Dynesius, M. and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266(4): 753-762.

Holzinger, T. 1998. Hydro-Québec plans, Hydro-Québec proposed new dams on native lands. Helio International, 4 May, 1998. Available from http://www.helio-international. org/Helio/anglais/practices/dams.html; Internet. Cited 3 September 2003.

Howatt, T. 2001. Hydro dams the future? NWT minister pitches revenue-making idea in Inuvik. Northern News Service, 21 August 2001.

Hydro-Québec. 2002. Eastmain-1 hydroelectric development. Hydro-Québec Production, Bulletin No. 1, updated November 2002. 4 p.

ICOLD. 2003. World Register of Dams 2003, computerized version. International Commission on Large Dams, Paris.

Industry Canada. 2003. Electrical power equipment and services; small-scale hydro. Available from http://strategis. ic.gc.ca/epic/internet/inmse-epe.nsf/vwGeneratedInterE/h_ep00020e.html; Internet. Cited 3 September 2003.

IPCC. 2001. Climate change 2001, impacts, adaptation, and vulnerability. *In* J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (ed.), Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK. 1032 p.

Jansson, R. 2002. The biological cost of hydropower. Coalition Clean Baltic, CCB Report No. 2002:2. 11 p.

Jansson, R., C. Nilsson, M. Dynesius and E. Andersson. 2000. Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. Ecol. Appl. 10(1): 203-224.

Jolley, W. (Senior Dam Safety Officer, Land and Water British Columbia Inc., Victoria, Canada). Personal communication, 15 July 2002.

Lavallée, D. (Centre d'espertise hydrique du Québec, Service de la Sécurité des barrages, Gouvernement du Québec). Personal communication, 29 October 2002.

Legault, H.L., T.L. Baldini, P. Béland, S.B. Bayh, F. Murphy and A. Chamberlain. 1998. Unsafe dams? A report by the IJC. A report to the government of the United States and Canada on the safety of dams and dykes which are subject to International Join Commission Orders, February 1998. Available from: www.ijc.org/comm/safedam/unsafe.html; Internet. Cited 3 September 2003.

Lett, D. and P. Samyn. 2003. Dam nears final hurdle: feds kick in $300,000 for technical study of hydro megaproject. Winnipeg Free Press, June 19, 2003, Winnipeg, Man., Canada.

Martin, T. 2001. Pearl Harbor – lessons for the dam safety community, p. 285-294. *In* Proceedings, Canadian Dam Association Annual Conference, 30 September - 4 October 2001, Fredericton, N.B.

Mathur, D., W.H. Bason, E.J. Purdy Jr. and C.A. Silver. 1985. A critique of the Instream Flow Increment Methodology. Can. J. Fish. Aquat. Sci. 42: 825-831.

Milburn, D., D.D. MacDonald, T.D. Prowse and J.M. Culp. 1999. Ecosystem Maintenance Indicators for the Slave River Delta, Northwest Territories, p. 329-348. *In* Y.A. Pykh, D.E. Hyatt and R.J.M. Lenz (ed.), Environmental indices, systems analysis approach. EOLSS Publishers Co. Ltd., Oxford, U.K.

Natural Resources Canada. 2000. Hydroelectric energy resource assessment. Available from http://www.canren.gc.ca/resou_asse/index.asp?CaId=54&PgId=274; Internet. Cited 3 September 2003.

Neu, H.J.A. 1982a. Man-made storage of water resources-a liability to the ocean environment? Part I. Mar. Pollut. Bull. 13: 7-12.

Neu, H.J.A. 1982b. Man-made storage of water resources-a liability to the ocean environment? Part II. Mar. Pollut. Bull. 13: 44-47.

Nilsson, C., R. Jansson and U. Zinko. 1997. Long-term responses of river-margin vegetation to water-level regulation. Science 276: 798-800.

Petts, G.E. 1984. Impounded rivers: perspectives for ecological management. Wiley-Interscience, John Wiley and Sons, Chichester. 326 p.

Poff, N.L. and D.D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience 52(8): 659-668.

Pohl, M.M. 2002. Bringing down our dams: trends in American dam removal rationales. J. Amer. Water Resour. Assoc. 38(6): 1511-1519.

Power, M.E., R.J. Stout, C.E. Cushing, P.P. Harper, F.R. Hauer, W.J. Matthews, P.B. Moyle, B. Statzner and I.R. Wais de Badgen. 1988. Biotic and abiotic controls in river and stream communities. J. N. Amer. Benthol. Soc. 7: 456-479.

Prowse, T.D. 1994. The environmental significance of ice to cold-regions streamflow. Freshwater Biol. 32(2): 241-260.

Prowse, T.D. 2001a. River-ice ecology: part A) hydrologic, geomorphic and water-quality aspects. J. Cold Regions Eng. 15(1): 1-16.

Prowse, T.D. 2001b. River-ice ecology: part B) biological aspects. J. Cold Regions Eng. 15(1): 17-33.

Prowse, T.D. and M. Conly. 1996. Impact of flow regulation on the aquatic ecosystem of the Peace and Slave Rivers. Northern Rivers Basin Study, Edmonton, Canada, Synthesis Report No. 1. 168 p.

Rosa, L.P. and M.A. dos Santos. 2000. Certainty and uncertainty in the science of greenhouse gas emissions from hydroelectric reservoirs, Part II. World Commission on Dams Thematic Review, Environmental Issues II.2., Secretariat of the World Commission on Dams, Cape Town, South Africa.

Rosenberg, D.M., F. Berkes, R.A. Bodaly, R.E. Hecky, C.A. Kelly and J.W.M. Rudd. 1997. Large-scale impacts of hydroelectric development. Environ. Rev. 5: 27-54.

Rosenberg, D.M., P. McCully and C.M. Pringle. 2000. Global-scale environmental effects of hydrological alterations: introduction. Bioscience 50(9): 746-751.

Stalnaker, C., B.L. Lamb, J. Henricksen, K. Bovee and J. Bartholow. 1995. The instream flow incremental methodology – a primer for IFIM. National Biological Service, U.S. Department of the Interior Biological Report 29, Washington, DC. 49 p.

St. Hilaire, A. and M. Leclerc (ed.). 2003. State-of-the-art in habitat modelling and conservation flows. Special Issue Can. Water Resour. J. 28(2): 133-336.

St. Louis, V.L., C.A. Kelly, E. Duchemin, J.W.M. Rudd and D.M. Rosenberg. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. BioScience 50(9): 766-775.

The Aspen Institute. 2002. Dam removal, a new option for a new century. The Aspen Institute Program on Energy, the Environment, and the Economy. Queenstown, Md., U.S.A. 68 p.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1(4): 6-10.

Walder, G.L. 1996. Proceedings of the Northern River Basins Study Instream Flow Needs Workshop, 14-15 October 1993 and 6-7 January 1994. Northern River Basins Study Report No. 66, Alberta Environment, Edmonton, Canada.

Ward, J.V. and J.A. Stanford. 1989. The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic systems, p. 347-356. *In* T.D. Fontaine and S.M. Baretell (ed.), Dynamics of lotic ecosystems. Ann Arbor Science. Ann Arbor, U.S.A.

Warren, L.A. and A.P. Zimmerman. 1993. Trace metal suspended particulate matter associations in a fluvial system: physical and chemical influences, p. 127-155. *In* S. Rao (ed.), Particulate and matter and aquatic contaminants. Lewis Publishers, Boca Raton.

Watt, W.E. (ed.). 1989. Hydrology of floods in Canada: a guide to planning and design. National Research Council of Canada, NRCC No. 29734. 245 p.

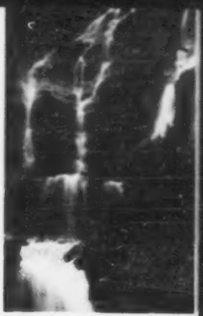
Wells, P.G. 1999. Environmental impacts of barriers on rivers entering the Bay of Fundy: report of an ad-hoc Environment Canada Working Group. Technical Report Series No. 334. Canadian Wildlife Service.

World Commission on Dams. 2000. Introduction to Global Change, Working Paper of the World Commission on Dams, Secretariat of the World Commission on Dams, Cape Town, South Africa.

Zhou, R.D. and C.R. Donnelly. 2002a. The impact of dam removal on instream sediments. *In* Proceedings, Canadian Dam Association Annual Conference, 7-9 October 2002, Victoria, B.C.

Zhou, R.D. and C.R. Donnelly. 2002b. Evaluating the impact of climate change on dam safety. *In* Proceedings, Canadian Dam Association Annual Conference, 7-9 October 2002, Victoria, B.C.

Zielinski, P.A. 2001. Flood frequency analysis in dam safety assessment, p. 79-86. *In* Proceedings, Canadian Dam Association Annual Conference, 30 September - 4 October 2001, Fredericton, N.B.



Chapter 3

DROUGHTS

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Current Status

Since most human activities and ecosystem health are dependent on reliable, adequate water supplies, droughts present a serious national threat to Canada. Large-area droughts have major impacts on a wide range of water-sensitive sectors including agriculture, industry, municipalities, recreation, and aquatic ecosystems. They often stress water supplies by depleting soil moisture reserves, reducing streamflows, lowering lake and reservoir levels, and diminishing groundwater supplies. This in turn affects several economic activities: for example, decreased agricultural production, less hydroelectric power generation, and increased marine transportation costs. In addition, droughts have major environmental implications such as reduced water quality, wetland loss, soil erosion and degradation, and ecological habitat destruction.

Droughts are complex phenomena with no standard definition. Simply stated, drought is a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (AES Drought Study Group, 1986). However, each drought is different depending on factors such as area affected, duration, intensity, antecedent conditions, and a region's capability to adapt to water shortages. Droughts also differ from other threats (e.g., floods) since they have long durations, and lack easily identified onsets and terminations. Furthermore, their recurrence in drought-prone areas is practically certain since drought is characteristic of dry environments (Maybank et al., 1995). Droughts occur on a variety of temporal and spatial scales with their impacts dependent on timing and sequencing of dry periods. For example, a shortage of water and soil moisture at a critical time for crop growth may initiate agricultural drought, but hydropower generation would not be affected if reservoirs have adequate supplies. Climate anomalies that last from a month to years are the root of most droughts; however, human impacts on resources and climate and changing demands for water are also major contributing factors (McKay et al., 1989).

Droughts in Canada

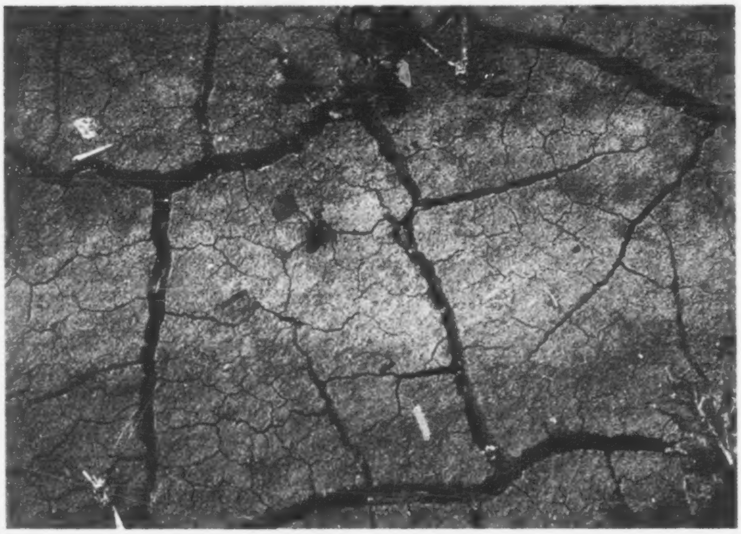
Although most regions of Canada have experienced drought, the Canadian Prairies (and to a lesser extent, interior British Columbia) are more susceptible mainly due to their high variability of precipitation in both time and space. During the past two centuries, at least 40 long duration droughts have occurred in western Canada. In southern regions of Alberta, Saskatchewan, and Manitoba, multi-year droughts were observed in the 1890s, 1930s, and 1980s (Phillips, 1990; Wheaton, 2000). Droughts in eastern Canada are usually shorter, smaller in area, less frequent, and less intense; nonetheless, some major droughts have occurred during the 20th century. In 1963/64 in southern Ontario, for instance, several wells ran dry, necessitating shipping of water from other areas. Great Lakes' water levels also fell to extreme lows with major losses incurred by the shipping industry (Gabriel and Kreutzwiser, 1993; Brotton, 1995). Droughts in the Atlantic Provinces occur even less frequently, but reduced occurrence results in lower adaptive capacity, making the region more susceptible to drought impacts (Nova Scotia Department of Agriculture and Fisheries, 2001). Droughts are less of a concern for northern Canada mainly due to their lower population densities; nevertheless, increased frequencies of forest fires during drought years can have serious economic impacts.

The recent 2001/02 drought was unusual in terms of its vast spatial extent. Intense dry conditions encompassed most of southern Canada extending from British Columbia, through the Prairies, into the Great Lakes-St. Lawrence region and even the Atlantic Provinces. Over much of the Prairies, several consecutive seasons of below average precipitation have led to one of the most severe prairie droughts on record, devastating many water-related resources in 2001 and 2002. In 2001, the aggregate level of the Great Lakes plunged to its lowest point in more than 30 years, with lakes Superior and Huron displaying near record lows (Mitchell, 2002). Over Atlantic Canada, three consecutive years of drought conditions have forced Nova Scotia to seek advice from the Prairie Farm Rehabilitation Administration (PFRA) on procedures to augment on-site water supplies for agricultural communities.

Causes

Droughts are the result of disruptions to an expected precipitation pattern and can be intensified by anomalously high temperatures that increase evaporation. The major factor in the onset and perpetuation of drought involves circulation patterns in the upper atmosphere. Over Canada, the most extreme warm-season droughts are associated with a persistent upper-air ridge of large amplitude over the affected area. This flow pattern creates "blocking conditions" that displace the jet stream, cyclonic tracks, and moist air masses and fronts (Chakravarti, 1976; Dey, 1982; AES Drought Study Group, 1986). Droughts can also be initiated and/or perpetuated during the cold season when a lack of precipitation results in lower than normal spring runoff and, thus, in reduced streamflow and reservoir and soil moisture replenishment. These precipitation deficiencies are also caused by anomalous upper-atmospheric circulation patterns and, in particular, a split in the jet stream over North America (e.g., Shabbar et al., 1997).

Several studies have found relationships between sea surface temperatures (SSTs) over various regions of the globe and large-scale atmospheric patterns with associated temperature and precipitation anomalies over Canada. For example, significant relationships between El Niño - Southern Oscillation (ENSO) and winter/early spring temperature and precipitation patterns for several regions of the country have been identified (Shabbar and Khandekar, 1996; Shabbar et al., 1997). Associations between North Pacific SSTs and atmospheric ridging over the Prairies leading to more intense droughts during the growing season have also been shown (Bonsal et al., 1993; Bonsal and Lawford, 1999). However, these summer relationships are much less robust as compared to winter. Relationships between Canadian temperature and precipitation and other large-scale oscillations such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) are also evident during the winter season (e.g., Bonsal et al., 2001a). Droughts tend to persist in that warm, dry springs are followed by hot, dry summers. In addition, there appears to be a tendency for warm summers to follow other warm summers, and so on. Reasons for this are not clear but are likely related to feedback processes that enhance or prolong drought situations (e.g., soil moisture anomalies) (Maybank et al., 1995).



Droughts present a serious threat to water quantity in Canada and thus impact a wide range of water-sensitive sectors including agriculture, industry, municipalities, recreation, and aquatic ecosystems.

Monitoring, Modelling, and Prediction

Real-time reports of lake and reservoir levels, streamflows, snowpack accumulations, water-supply volume forecasts, dugout water levels (for the Prairies), and precipitation anomalies are currently used for drought monitoring in Canada. The status of these water supplies is critical to activities such as irrigation, water apportionment, storage, flood forecasting, hydroelectric power generation, navigation, fisheries, and wetland habitat. In the Canadian Prairies, provincial water resource agencies have been publishing monthly reports of stream, lake, reservoir, and groundwater levels since the late 1970s. Pasture conditions, on-farm surface water supplies, and seasonal precipitation accumulations are monitored by Agriculture and Agri-Food Canada (AAFC). AAFC maintains the *Drought Watch* web site that provides real-time information on prairie drought conditions, and promotes practices to reduce drought vulnerability. The Canada-wide drought of 2001 prompted the expansion of *Drought Watch* to monitor the risk and status of drought over the major agricultural regions of the country. A national map illustrating precipitation accumulations is now prepared in collaboration with the Meteorological Service of Canada (MSC).

Numerous indices that are measures of drought severity are also used for monitoring and modelling drought conditions. These range from simple approaches that only consider precipitation, to more complex indices incorporating a water balance approach using precipitation, potential evapotranspiration, antecedent soil moisture, and runoff (e.g., the Palmer Drought Severity Index [PDSI]; Palmer, 1965). Various soil moisture indices have also been used to monitor and model soil moisture changes from daily precipitation and actual evapotranspiration. A problem with these more complex indices is that evapotranspiration is difficult to compute since it relies on meteorological measurements that are generally not readily available (net radiation, vapour pressure deficit, wind speed). The high spatial variability of summer convective rainfall and the difficulties in modelling snowmelt and blowing snow also hinder regional-scale moisture modelling (Maybank et al., 1995). There are currently several meteorological and surface water indices under investigation and/or consideration for use over all of Canada. Plans are underway to incorporate these indices to monitor near real-time drought conditions across the entire country, similar to the Drought Monitor project in the United States (Svoboda et al., 2002). Satellite and radar measurements can potentially provide solutions to the spatial-scale problems associated with drought monitoring and modelling. MSC currently uses Special Sensor Microwave Imager (SSMI) to produce snow water equivalent maps for the Prairie Provinces, available to water resource agencies.

Drought prediction involves anticipating climatic anomalies that produce unusually dry conditions for an extended period of time; however, at present, there is no completely satisfactory method that can routinely predict Canadian climate over the month to season time frame required for drought analysis. Environment Canada currently produces seasonal forecasts for temperature and precipitation for lead times of 3, 6, 9, and 12 months using both statistical and numerical weather modelling techniques. The forecasts are updated quarterly at the national scale but this is often too infrequent for regional and local drought analyses.

Adaptation

Adaptation involves adjusting to climate change, variability, and extremes to avoid or alleviate negative impacts and benefit from opportunities (Watson et al., 2001). Drought adaptations include short- to long-term actions, programs, and policies implemented both during and in advance of drought to help reduce risks to human life, property, and productive capacity (Wilhite, 2000). Canadians have a great deal of experience in adapting to droughts; however, their adaptation strategies vary by sector and location. Areas with a greater risk of droughts are often better prepared to deal with dry conditions. Drought adaptation decisions are made at a variety of levels ranging from individuals, to groups and institutions, to local and national governments. There are various adaptation processes or strategies including sharing and/or bearing the loss, modifying drought effects, research, education, behavioural changes, and avoidance (Burton et al., 1993). Adaptive drought measures include soil and water conservation, improved irrigation, and construction of infrastructure, including wells, pipelines, dugouts and reservoirs, and exploration of groundwater supplies. The usefulness of each set of strategies varies with location, sector, and the nature and timing of the drought. Better management responses may be made with improved drought and drought impacts monitoring and advanced prediction. Adjustments that occur after drought are generally less effective than planned anticipatory adaptation.

Drought adaptation research and planning strategies are in their early stages although risk management plans for drought-prone regions of the country have been established (e.g., the Agriculture Drought Risk Management Plan for Alberta). Many adaptive strategies have been devised and tested for their effectiveness in reducing drought impacts (Maybank et al., 1995). However, intense, large-area droughts that persist for several years still result in severe hardship, even to those regions used to coping with droughts. An improved capability to estimate the numerous impacts associated with drought is required for enhanced adaptation. In addition, future national, provincial, and municipal level coordinated and proactive drought planning is needed, since vulnerability to future droughts could be exacerbated by increasing development, as well as by increased summer drying and risk of drought projected to occur over most mid-latitude continental interiors as a result of climate change (Watson et al., 2001).

Trends and Variability

There has been some effort to define large-scale trends and variability in Canadian temperature and precipitation, and, to a lesser extent, various drought-related indices during the period of instrumental record. With regard to the latter, results have generally shown substantial decadal-scale variability with no consistent trends in terms of frequency, duration, or severity of droughts during the 20th century. A problematic issue for most of these trend analyses is that they have been carried out independently with limited attempts to derive comprehensive results for the entire country. Also, they often differ in terms of starting dates for trend calculation, and with respect to initial conditions for determining drought indices. Furthermore, the limitation of the instrumental record to approximately the last 100 years, combined with sparse high-resolution paleo-climatic information in areas most prone to drought, makes inference into long-term trends in Canadian droughts very difficult. Selected examples of trends and variability in various drought-related parameters are provided below.

High surface temperatures can intensify drought conditions through enhanced evaporation in summer and increased sublimation and melting of the snowpack during winter. Several studies have shown significant trends in temperature and various temperature-related indices over Canada during the 20th century. Mean annual air temperature has increased by an average of 0.9°C over southern Canada for the period 1900-98 (Fig. 1). The greatest warming was observed in the West and the largest rates occurred during winter and especially spring (Zhang et al., 2000). Much of the country has also experienced significant trends toward longer frost-free periods (Bonsal et al., 2001b). This could affect drought occurrence since these trends translate into a longer ice-free season for lakes and rivers, thus increasing the potential for open-water evaporation. From 1900-98, annual precipitation has significantly increased over most of southern Canada, with the exception of southern Alberta and Saskatchewan (Fig. 1). This pattern is also generally evident during all seasons within the year (Zhang et al., 2000). The period 1915-97 was associated with substantial interdecadal variability in North American snow cover, including lowest snow cover anomalies in the 1920s and 1930s and highest during the late 1970s and early 1980s. Coincident with the large increases in spring temperature, the 1980s/90s were characterized by rapid reductions in snow cover during the second half of the snow season and especially in April (Brown, 2000).

Examples of 20th century PDSI time series for various regions of the country are provided in Fig. 2 (Skinner, 2002). Negative PDSI represent drought-like conditions. The series show considerable decadal-scale variability

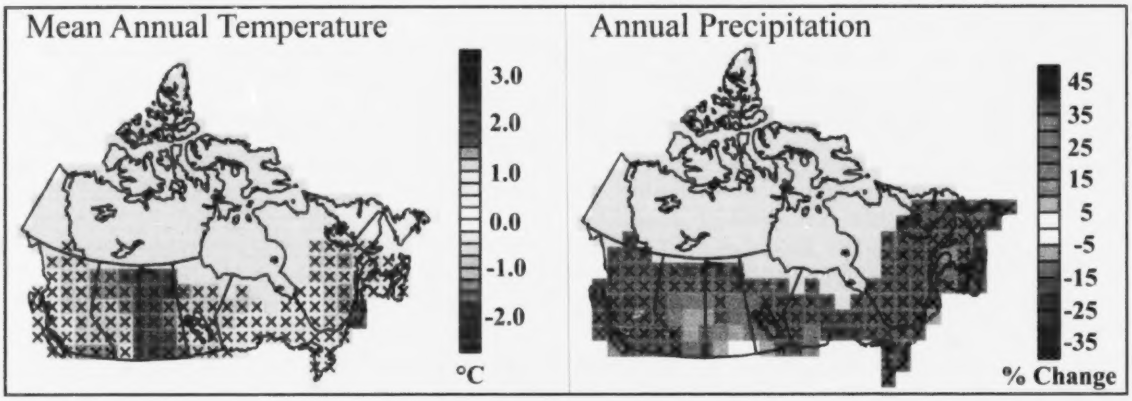


Fig. 1. Trends in mean annual temperature (°C/99-year period) and total annual precipitation (% change/99-year period) over southern Canada from 1900-98. Grid squares with trends statistically significant at the 5% level are denoted by crosses (taken from Zhang et al., 2000).

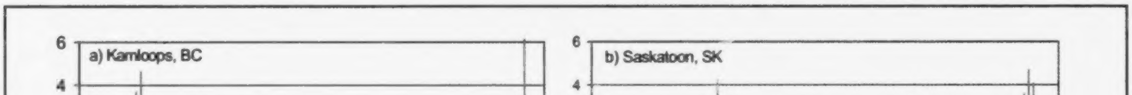


Fig. 2. Annual PDSI values for a) Kamloops, BC, b) Saskatoon, SK, c) Sherbrooke, QC, and d) Yarmouth, NS. Solid lines represent 10-year running means (source: Climate Research Branch, Meteorological Service of Canada, Environment Canada, Downsview, ON).

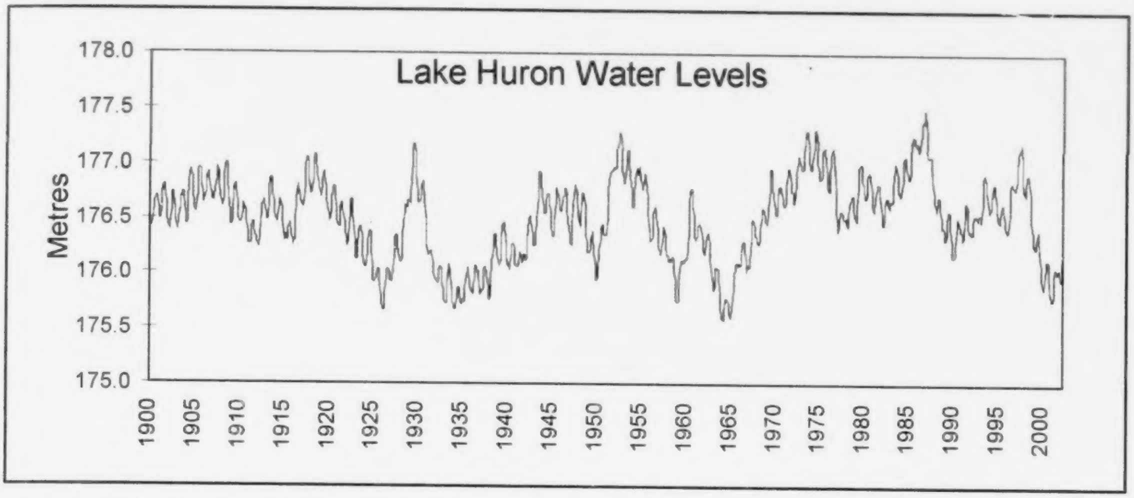


Fig. 3. Annual lake levels for Lake Huron for the period 1900-2001 (source: Environment Canada, Water Issues Division, Burlington, ON).

with no long-term trends discernible in any portion of the country. All four graphs, however, do show the large-area drought conditions observed over much of Canada during late 1990s to early 2000s. Sauchyn and Skinner (2001) reconstructed July PDSI for the southwestern Canadian Plains using tree ring chronologies dating back to 1597. Results showed that the 20th century lacked the prolonged droughts of the 18th and 19th centuries when the PDSI was consistently below zero for decades at a time. Clusters of drought years in the series suggest the existence of a 20- to 25-year periodicity over this region.

In terms of large-scale circulation, Skinner et al. (1999) identified an increasing trend in 500 hPa heights over much of Canada with an amplification of the western Canadian ridge and an eastward shift of the Canadian Polar Trough for the period 1953-1995. Many large-scale atmospheric and oceanic oscillations such as the PDO and NAO generally revealed considerable interannual and interdecadal variability during the last century. El Niño events, however, have tended to be more frequent and intense in the last 20 to 30 years and some models are projecting more El Niño-like conditions in the future (e.g., Timmermann et al., 1999). This could affect winter drought conditions since El Niño has been shown to be associated with warmer, drier winters over most of southern Canada (Shabbar and Khandekar, 1996; Shabbar et al., 1997).

There have been some analyses of trends and variability in various water-related drought indicators over Canada, but these records tend to be much shorter. Over the last 30 to 50 years, mean streamflow has decreased in many parts of Canada with significant reductions in southern regions of the country (Zhang et al., 2001). Great Lakes' water levels have shown considerable variability during the 20th century. For example, Fig. 3 reveals several decadal-scale periodicities in Lake Huron levels with no evidence of any long-term trend. Lower levels coincided with the droughts of the 1930s, early 1960s, and the most recent 1999-2001 dry period. Over the Prairies, the numbers and water levels of wetlands have shown no clear trend over the last 40 to 50 years (Conly and van der Kamp, 2001).

All Global Climate Models are projecting future increases of summer continental interior drying and associated risk of droughts. The increased drought risk is ascribed to a combination of increased temperature and potential evaporation not being balanced by precipitation (Watson et al., 2001). However, considerable uncertainty exists with respect to future precipitation, particularly on a regional and intra-seasonal basis. Furthermore, relatively little is known regarding changes to large-scale circulation and, since these patterns have a significant impact on temperature and precipitation over Canada, the occurrence of future drought remains a huge knowledge gap.

Knowledge Gaps and Program Needs

There are several gaps in the knowledge of droughts that limit our ability to understand their occurrence, monitor/model their status, and adapt to their negative effects. The following identifies major research and program needs regarding droughts in Canada.

Occurrence of Droughts

A better understanding of the physical causes and characteristics of past droughts including their spatial and temporal variability is required. This understanding will provide improved insight to short-term (seasonal to annual) and long-term (decade to century) projections of future droughts in Canada. In particular, we require:

- improved knowledge of drought trends and variability prior to the instrumental record. This requires more research into reliable proxy indicators to reconstruct drought occurrence over various regions of Canada for the last few hundred years;
- improved understanding of the physical causes of drought initiation, persistence, and termination during the last few hundred years. This includes:
    - the role of large-scale atmospheric and oceanic oscillations in the initiation and persistence of anomalous circulation patterns responsible for drought, particularly during the summer season
    - impacts of soil moisture anomalies on the perpetuation and migration of drought
    - physical causes of multi-year droughts and their recurrence on decadal time scales
    - atmospheric circulation patterns associated with unusually large spatial-scale droughts (e.g., the 2001 drought over most of southern Canada), and
    - atmospheric conditions responsible for the termination of a drought including aspects such as convective rainfall, precipitation trigger mechanisms, and moisture sources;
- better knowledge regarding the occurrence of future droughts in terms of likely areas to be affected and potential changes to their frequency, duration, and severity. This requires:
    - more reliable future climate simulations (particularly precipitation) from Global and Regional Climate Models
    - improved downscaling methods for application of climate model data to appropriate spatial and temporal scales, and
    - knowledge of future changes to large-scale circulation patterns and oscillations such as ENSO, PDO, and the NAO.

Monitoring, Modelling, and Prediction

The ability to predict drought onset, intensity, and termination more accurately requires improvements in modelling and monitoring of current drought conditions, as well as better short-term (seasonal) climate forecasts. The following are needed to improve our capability to monitor, model, and predict droughts in Canada:

- improved accessibility to past and near real-time meteorological data
- restoration and expansion of the climate station network to provide adequate spatial coverage of meteorological observations over the country
- development of a total water supply database including, for example, improved data of streamflow records, wetland numbers, and groundwater supplies
- development of an index or combination of indices to monitor past and near real-time drought conditions and to aid in recognition of drought sufficiently in advance. Standard indices would allow for national-scale evaluations of drought
- better understanding of the amount and distribution of groundwater resources including linkages to climate and surface water supply
- development of better methodologies to incorporate remote sensing and ground-level radar for drought monitoring and management (to augment the climate station network). The geospatial and temporal capacity of satellite imagery offers many opportunities for advanced monitoring capabilities
- incorporation of existing Geographical Information System (GIS) techniques to provide better spatial representations of drought. For example, the migration patterns of drought and its associated synoptic circulation patterns could be tracked on a variety of temporal scales
- better hydrologic modelling techniques and, in particular, improved methodologies to estimate evapotranspiration
- improved integration of Global and Regional Climate Models with distributed water balance models in order to model future drought conditions, and
- more reliable short-term (seasonal) forecasts of temperature and precipitation at the appropriate spatial scales to aid in prediction of drought onset, intensity, persistence, and termination.

Impacts and Adaptation

Droughts are certain to recur in the future. As a result, more effective short- and long-term adaptation strategies are required to defend against these future droughts including improved technological, monitoring, and predictive capabilities. Additional requirements include:

- more rapid updates of potential drought conditions to activate drought response and adaptation options
- identification of ecosystem thresholds to determine at what point during a drought adaptation options should be activated to avoid serious or irreversible losses. The same applies to economic thresholds
- more research into understanding and modelling of drought adaptation measures, including their effectiveness, practicality, costs, and benefits
- improved knowledge regarding adaptation to prolonged droughts including those that may result from climate change
- better abilities to assess adequately the socio-economic consequences of alternative drought adaptation strategies.

References

AES Drought Study Group. 1986. An applied climatology of drought in the Canadian Prairie Provinces. Report No. 86-4, Canadian Climate Centre, Downsview, ON. 197 p.

Bonsal, B.R., A.K. Chakravarti and R.G. Lawford. 1993. Teleconnections between north Pacific SST anomalies and growing season extended dry spells on the Canadian Prairies. Int. J. Climatol. 13: 865-878.

Bonsal, B.R. and R.G. Lawford. 1999. Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian Prairies. Int. J. Climatol. 19: 1445-1458.

Bonsal, B.R., A. Shabbar and K. Higuchi. 2001a. Impacts of low frequency variability modes on Canadian winter temperature. Int. J. Climatol. 21: 95-108.

Bonsal, B.R., X. Zhang, L.A. Vincent and W.D. Hogg. 2001b. Characteristics of daily and extreme temperatures over Canada. J. Climate 14: 1959-1976.

Brotton, J. 1995. Causes and impacts of 1960s low water levels on Canadian Great Lakes interests: phase 2 report. Report prepared for Environment Canada, Environmental Adaptation Research Group, Burlington, ON. 60 p.

Brown, R.D. 2000. Northern hemisphere snow cover variability and change, 1915-97. J. Climate 13: 2339-2355.

Burton, I., R.W. Kates and G.F. White. 1993. The environment as a hazard. The Guilford Press, New York. 290 p.

Chakaravarti, A.K. 1976. Precipitation deficiency patterns in the Prairie Provinces of Canada. Prairie Forum – The Journal of the Canadian Plains Research Centre 1: 95-110.

Conly, F.M. and G. van der Kamp. 2001. Monitoring the hydrology of Canadian Prairie wetlands to detect the effects of climate change and land use changes. J. Environ. Monitor. Assess. 67: 195-215.

Dey, B. 1982. Nature and possible causes of droughts on the Canadian Prairies - case studies. J. Climatol. 2: 233-249.

Gabriel, A.O. and R.D. Kreutzwiser. 1993. Drought hazard in Ontario: a review of impacts, 1960-1989, and management implications. Can. Water Resour. J. 18: 117-132.

Maybank, J., B.R. Bonsal, K. Jones, R.G. Lawford, E.G. O'Brien, E.A. Ripley and E. Wheaton. 1995. Drought as a natural disaster. Atmosphere-Ocean 33: 195-222.

McKay, G.A., R.B. Godwin and J. Maybank. 1989. Drought and hydrological drought research in Canada. Can. Water Resour. J. 14: 71-84.

Mitchell, J.G. 2002. Down the drain? The incredible shrinking Great Lakes, p. 37-51. National Geographic, September 2002.

Nova Scotia Department of Agriculture and Fisheries. 2001. Estimated impact of 2001 drought on agriculture in Nova Scotia. Nova Scotia Department of Agriculture and Fisheries, Halifax, NS.

Palmer, W.C. 1965. Meteorological drought. U.S. Weather Bureau, Research Paper 45, Washington, DC. 58 p.

Phillips, D. 1990. The climates of Canada. Environment Canada, Ottawa, ON. 176 p.

Sauchyn, D.J. and W.R. Skinner. 2001. A proxy record of drought severity for the southwestern Canadian Plains. Can. Water Resour. J. 26: 253-272.

Shabbar, A., B.R. Bonsal and M. Khandekar. 1997. Canadian precipitation patterns associated with the Southern Oscillation. J. Climate 10: 3016-3027.

Shabbar, A. and M. Khandekar. 1996. The impact of El Niño-Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean 34: 401-416.

Skinner, W.R. 2002. Update on western Canada drought: the Palmer Drought Severity Index. Unpublished report.

Skinner, W.R., B.J. Stocks, D.L. Martell, B.R. Bonsal and A. Shabbar. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theoret. Appl. Climatol. 63: 89-105.

Svoboda, M., D. LeComte, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, R. Tinker, M. Palecki, D. Stooksbury, D. Miskus and S. Stephens. 2002. The drought monitor. Bull. Amer. Meteorolog. Soc. 83: 1181-1190.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif and E. Roeckner. 1999. Increased El Nino frequency in a climate model forced by future greenhouse warming. Nature 398: 694-696.

Watson, R.T. and the Core Writing Team. 2001. Climate change 2001: synthesis report. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK. 34 p.

Wheaton, E.E. 2000. Canadian prairie drought impacts and experiences, p. 312-330. *In* D. Wilhite (ed.), Drought: a global assessment, Volume I. Routledge Press, London, UK.

Wilhite, D. 2000. Drought as a natural hazard: concepts and definitions, Part I. *In* D. Wilhite (ed.), Drought: a global assessment, Volume I. Routledge Press, London, UK.

Zhang, X., K.D. Harvey, W.D. Hogg and T.R. Yuzyk. 2001. Trends in Canadian streamflow. Water Resour. Res. 37: 987-998.

Zhang, X., L.A. Vincent, W.D. Hogg and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38: 395-429.

Chapter 4

FLOODS

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Current Status

Flooding in Canada is primarily but not exclusively caused by hydro-meteorological conditions, either individually or in combination (Watt, 1989; Andrews, 1993), which can occur in the form of excess snowmelt-runoff, rain, rain on snow, ice-jams, or natural dams. Anthropogenic causes of flooding include changes in drainage patterns resulting from urbanization and flooding due to dam-breaks. Brooks et al. (2001) note that over the last century, damages in Canada have exceeded $2 billion with over 198 lives lost. The recent devastating floods on the Saguenay River during the summer of 1996 and the Red River in the spring of 1997 have brought the reality of natural hazards home to Canadians. The Saguenay flood occurred due to an unprecedented precipitation event over a 24-hour period and resulted in more than $1 billion in damages and loss of 10 lives (Commission scientifique et technique sur la gestion des barrages, 1997). The "flood of the century" in southern Manitoba was caused by a combination of hydro-meteorological factors, beginning with high antecedent soil moisture, heavy winter snowfall, and a rapid spring melt. Although there was no direct loss of life, damages (including flood-fighting costs) were estimated at $500 million in Canada and over $2 billion in total (IJC, 2000). Infrequent, large flood events can also cross the erosive thresholds along alluvial rivers and result in catastrophic erosion along valley bottoms. Such erosion represents another major risk from flooding, in addition to the inundation damage from floodwaters, and it can result in significant losses of property and infrastructure, even when these are situated above the flood level.

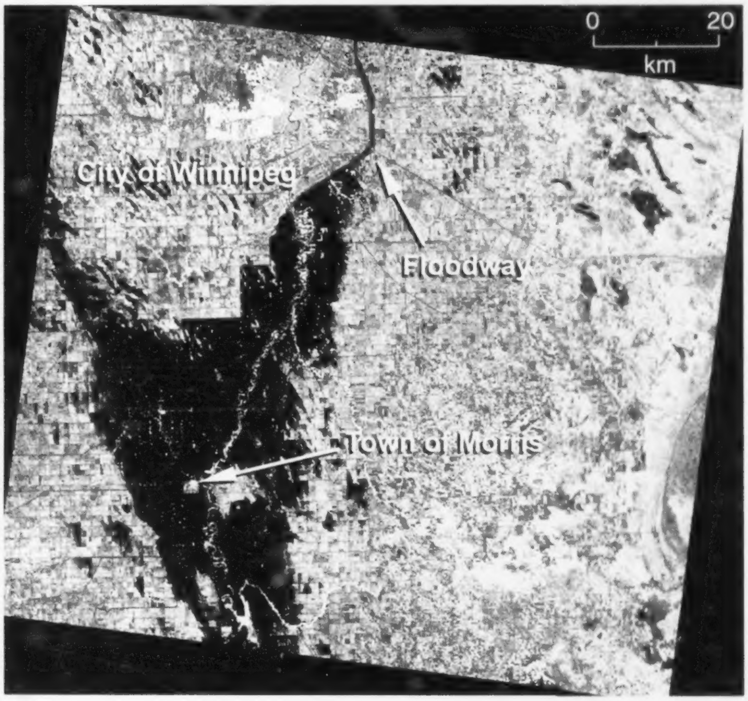
Public perception of flooding is often as a natural hazard that should be mitigated, and it is in this context that this chapter is written. It is important to understand, however, that there are beneficial ecological aspects of flooding that are often not considered, yet which are an important component of ecological sustainability. For example, changes in the flooding regime of the Peace-Athabasca Delta in northern Alberta have been attributed to a decrease in ice-jam frequency due to climatic changes and river regulation (Prowse and Conly, 1996). These changes, in turn, have resulted in a decline of fish and wildlife habitats and disruption of the entire ecosystem; hence, a change in flooding regime can have significant ecological impacts. Such impacts are not considered for this chapter, however, and the focus is confined to flooding as a natural hazard.

Adaptation and Mitigation

From the earliest settlements in Canada, people have chosen to live and work along rivers and lakes. Apart from their obvious value as a source of drinking water, these water bodies also supply a source of irrigation and power and a means of transportation, while the riverbank and floodplains provide aesthetically pleasing sites for housing and easy access for industrial discharge. As encroachment into the natural floodplain has increased with population growth, so has the damage caused by flooding. Structural measures such as dams, dykes and diversions have been engineered to mitigate flood risks, giving residents a sometimes false sense of security; however, these measures also have the potential to disrupt riparian ecosystems. Non-structural approaches to reducing flood damages, including floodplain regulation and flood forecasting, have gained favour therefore, and they provide a sound mitigation strategy for reducing damages. In both the structural and non-structural approaches to mitigation and/or adaptation, thorough hydrological analysis is required, typically including flood-frequency analysis, hydraulic and hydrological modelling studies, and robust engineering design.

Floodplain regulation requires defining the floodplain at an elevation that provides an acceptable level of risk to residents living above the defined zone, and suitable use (e.g., public parks, recreation areas) of the flood zone. Floodplain delineation is typically based on a derived regulatory river flow. These flow rates are often based on frequency analysis (statistical properties) of historic streamflows at a specified river location (Burn, 2002); however, in ungauged regions, they can also be based on regional analysis and comparison of gauged and ungauged regions, or through application of a hydrological model to a known design storm. In all cases, resulting flows are used in concert with a hydraulic model to determine water surface elevations for the river-reach or location of interest. The resulting elevation along the river banks becomes the basis for most floodplain zoning and planning. At the time of the termination of the Federal-Provincial Flood Damage Reductions Program (FDRP), whose primary purpose was to map urban flood-prone lands, approximately 700 out of 1100 Canadian flood-prone communities were mapped (Shrubsole et al., 2003). Although, historically, the FRDP analysis included most of the high-risk communities in Canada, many Canadians remain unaware of their exposure to flood hazards.

Structural approaches to flood mitigation usually include multi-purpose structures such as large dams. These structures are more often designed for preserving low flows, hydro-power production and irrigation; however, they can often provide some protection of downstream communities from extreme events. Design of these structures requires analysis of potential large flows for adequate spillage and dam safety requirements. The Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) are criteria commonly used in design and safety analysis for all large dams in Canada (see discussion below). Any engineered flood control structure such as a dam, diversion or dyke must not only be designed appropriately, but must also be operated and maintained effectively.



Radarsat standard mode 6 image of the 1997 "Flood of the Century" near Winnipeg, Manitoba, acquired on May 1, 1997. The flood extent is clearly evident as is the ring dike around the town of Morris and the floodway providing protection for the City of Winnipeg. Copyright 1997 Canadian Space Agency. Data processed and distributed by Radarsat International; data enhancement and interpretation by Canada Centre for Remote Sensing.

Flood Forecasting

Flood forecasting is a key non-structural approach to reducing flood losses and is highlighted here because of its potential. Forecasting is typically achieved through application of one or more modelling systems and there are many hydrological and hydraulic models available for this purpose. Hydrological models range in sophistication from a simple statistical rainfall-runoff relationship to more detailed, physically based algorithms describing the complete rainfall-runoff system. Hydraulic models are also used in flood forecasting to calculate travel time of the flood wave and its attenuation. These models use the standard equations of unsteady, non-uniform flow with various simplifications depending on the channel characteristics, available data, and accuracy requirements. Probabilistic models that take data uncertainties into account are also available. Probabilistic models apply a statistical distribution to input parameters such as precipitation forecasts and produce a large number of model runs that are statistically analyzed. The resulting forecast provides an entire distribution of future plausible conditions rather than a single outcome.

Dam Safety

While aspects of dam safety are described in Chapter 2, for the purposes of this discussion the failure of a flood control dam resulting from an extreme flood is explored – currently a very important issue for many provincial flood management agencies. Such high consequence dams are often designed to withstand the PMF, defined by the U.S. Federal Energy Regulatory Commission (2002) as "the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study." Theoretically, the probability of exceeding the PMF is zero, and hence the dam can safely withstand all floods. The Canadian Dam Association's Dam Safety Guidelines provide a similar definition (Canadian Dam Association, 1998).

As the estimation of the PMF uses historical data, it is re-estimated periodically as more data are collected. Occasionally, the revised PMF becomes significantly use (e.g., public parks, recreation areas) of the flood zone. Floodplain delineation is typically based on a derived regulatory river flow. These flow rates are often based on frequency analysis (statistical properties) of historic streamflows at a specified river location (Burn, 2002); however, in ungauged regions, they can also be based on regional analysis and comparison of gauged and ungauged regions, or through application of a hydrological model to a known design storm. In all cases, resulting flows are used in concert with a hydraulic model to determine water surface elevations for the river-reach or location of interest. The resulting elevation along the river banks becomes the basis for most floodplain zoning and planning. At the time of the termination of the Federal-Provincial Flood Damage Reductions Program (FDRP), whose primary purpose was to map urban flood-prone lands, approximately 700 out of 1100 Canadian flood-prone communities were mapped (Shrubsole et al., 2003). Although, historically, the FRDP analysis included most of the high-risk communities in Canada, many Canadians remain unaware of their exposure to flood hazards.

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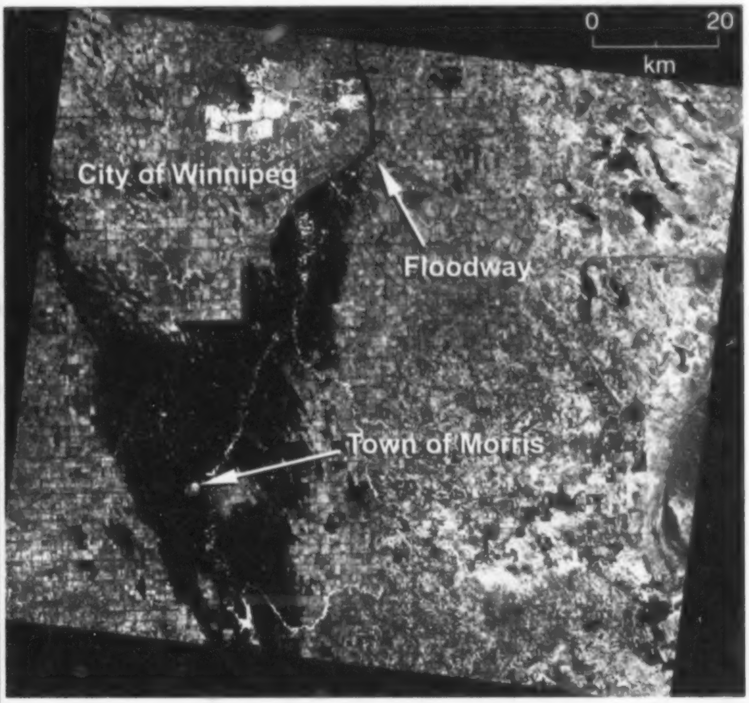

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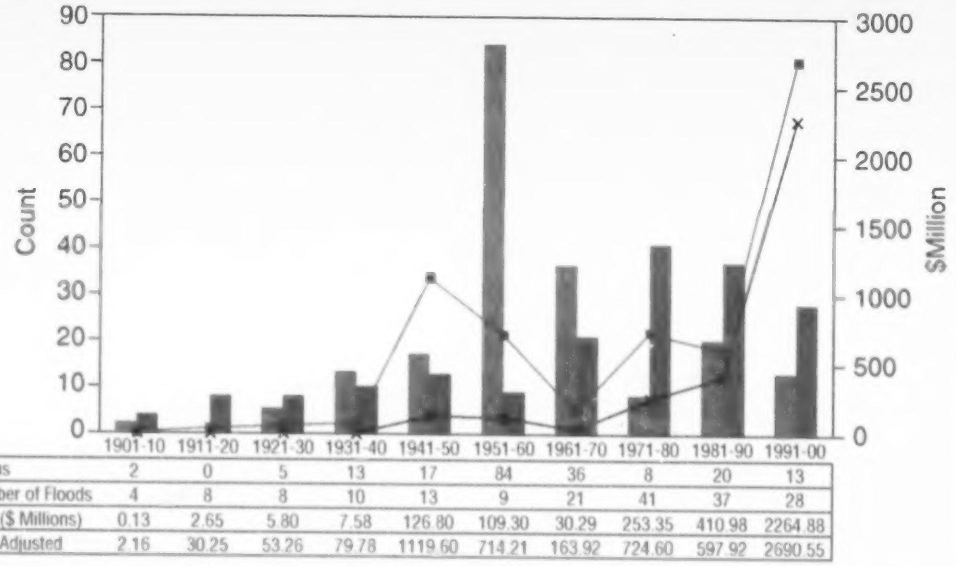


	1901-10	1911-20	1921-30	1931-40	1941-50	1951-60	1961-70	1971-80	1981-90	1991-00
▬ deaths	2	0	5	13	17	84	36	8	20	13
▬ Number of Floods	4	8	8	10	13	9	21	41	37	28
-✕- Cost ($ Millions)	0.13	2.65	5.80	7.58	126.80	109.30	30.29	253.35	410.98	2264.88
-■- Cost Adjusted	2.16	30.25	53.26	79.78	1119.60	714.21	163.92	724.60	597.92	2690.55

Fig. 1. Flood damages in Canada (after Brooks et al., 2001). Adjusted values based on Construction Price Index (Kulshreshtha, 2003).

higher as new data are added. For example, Jarrett and Tomlinson (2000) provided an example where the revised PMF for the Olympus Dam in Colorado was almost four times larger than the original estimate. When this situation occurs, the dams may fail the safety check, leading to expensive spillway re-design and re-construction. There is, therefore, a considerable amount of concern about the validity and robustness of techniques used for PMF estimation.

The PMF is often calculated as the flood generated by the most severe precipitation possible at a site at a particular time of year, referred to as the PMP. The World Meteorological Organization (WMO) commissioned a manual to describe techniques to estimate the PMP (World Meteorological Organization, 1986). The manual explains that the method for estimating the PMP cannot be standardized and may need to be modified for a particular region (World Meteorological Organization, 1986). The techniques depend on the size and location of the basin of interest, the amount and quality of data available at the site, and meteorological conditions that produce severe precipitation events. These problems are particularly severe in high-relief areas, such as the Coast Mountains in Canada and the United States, where due to orographic effects, strong precipitation gradients exist. For example, with the use of paleohydrology records, it has been shown that PMP estimates in mountainous regimes are generally too high (e.g., Parrett and Jarrett, 2000). The WMO manual states that the PMP must be considered an estimate and that its accuracy cannot be assessed in an objective manner (World Meteorological Organization, 1986). Therefore, these standard PMP procedures may need to be modified for a particular region. Also, the use of deterministic rather than statistical approaches to PMP and PMF estimation could receive some consideration. Abbs (1999) recommended that increased effort be placed on numerical modelling of extreme rainfall events.

Trends

Adaptation and Mitigation

Improvements in statistical methods along with technological advances in mapping have the potential to reinvigorate and renew mitigation strategies in many Canadian locations. The federal government currently has no role in floodplain management and some provincial governments have also terminated their programs, while others are applying the information obtained during the Flood Damage Reduction Program (FDRP) without modification. Of some concern is the fact that hydrological knowledge gained through improvements in understanding and longer observation periods in the last two decades has not been used to re-assess flood risks established under FDRP. If this situation continues, exposure to potential loss of life and property due to flooding may increase, as will the threat to federal resources in the form of federal disaster assistance. It would be prudent to examine flood risk in Canada in this context, as well as in light of new potential changes to hydrological regimes in Canada resulting from climate change.

In terms of improved flow analysis, there has been a recent tendency to incorporate regional analysis as opposed to single-site analysis for the estimation of flood frequency curves. As an example, the Flood Estimation Handbook (IH, 1999) recently developed in the U.K. incorporates a focused regionalization approach (Burn, 1990) for estimating at-site design flood magnitudes. Regrettably, there is no equivalent set of guidelines for Canada nor are there currently federal standards or guidelines for regional analysis. As such, different approaches, of varying levels of sophistication, are employed in different provinces.

Contemporary remote-sensing techniques, such as Light Detection and Ranging (Lidar) for elevation mapping, and global position technologies (GPS) in combination with Geographic Information Systems (GIS) provide an opportunity to re-engineer flood mapping strategies. It is now feasible to create an accurate representation of a floodplain quickly and at relatively low cost.

Forecasting and Models

Combining weather forecasts with information on watershed conditions and a hydrological streamflow forecasting model can give advanced warning (up to 48 hours) of potential flash-flooding and can help save lives and reduce property damage. Precipitation measurements and forecasts are the most uncertain inputs in a flood forecasting system. Over the last couple of decades, knowledge of atmospheric processes has improved, computers have become more powerful, and it has become possible to model the atmosphere numerically. There are several Canadian atmospheric models produced by the Canadian Meteorological Centre that can be used for short-term weather modelling, including the Regional Finite Element (RFE) model (Mailhot et al., 1998), the Global Environmental Multiscale (GEM) model (Côté et al., 1998), and the Mesoscale Compressible Community (MC2) model (Benoît et al., 1997). These models can operate in forecast mode, where initial atmospheric conditions are specified and the model physics are used to predict future weather conditions (currently, the GEM model is used for weather forecasts in Canada).

Coupling hydrological forecasts to a well-calibrated, high-resolution Numerical Weather Prediction (NWP) model not only offers a valid substitute for precipitation data, but, more importantly, it provides a means to compute forecasted river flows with forecasted precipitation data. Research has recently been completed to develop further the optimal coupling of a high-resolution regional atmospheric model (for example the Canadian MC2) with a hydrological model (WATFLOOD) for flood forecasting. To achieve this, a conceptual framework for model development was initiated using different degrees of model coupling to obtain a complete two-way coupled model. The first level of coupling is referred to as model linking and requires calibrating and validating the high-resolution regional atmospheric model and the distributed hydrological model separately. This form of coupling then uses the simulated precipitation from the atmospheric model to drive the hydrological model to study flash flood events. A real-time experiment was initiated under the Mesoscale Alpine Project (MAP) in 1999 to forecast flash floods in the European Alps using 24-hour NWP forecasts for precipitation and temperature (Kouwen and Benoit, 2002). Under this modelling scenario, the two models use their own inherent land surface scheme and parameterizations. The hydrologic model forcing is derived directly from the atmospheric forecasts with the dominant input being precipitation. This is of great interest as precipitation is the single most uncertain variable for such hydrological studies.

In order to achieve truly coupled systems, the link between the models (MC2 and WATFLOOD) was established by implementing a common land surface scheme (the Canadian Land Surface Scheme [CLASS]) in each model. This model development took place under the NSERC-funded Simulation of Severe Precipitation for Flood Forecasting (SSPFF) research program. Results were promising and showed the ability to predict adequately precipitation and streamflow for the Saguenay event of 1996. Since that time there have been advances in developing an independent system for coupling atmospheric and hydrological models that do not require the common land-surface scheme. A modelling framework described by Pietroniro and Soulis (2003) as part of the Mackenzie GEWEX study (MAGS) has provided a conceptual context for further advancements of these coupled models. An example of such a coupled modelling study for the 1996 Saguenay flood is Lin et al. (2002). This and other developments have the potential to advance both hydrological and atmospheric research while maintaining operational linkages. There have been tremendous gains in applying distributed hydrological models for flood forecasting, and often the major sources of uncertainty are the meteorological forcing variables, particularly precipitation.

Land-Use Impacts

There is a widely held public perception that urbanization and land-use changes in the upper basin have an influence on large floods. This may or may not be the case. Contemporary urban design usually requires that stormwater management systems in new subdivision development not lead to an increased runoff. Often this is administered by local bylaw. In the absence of such regulations, runoff increases can take place. Current-day land-use changes in rural areas, such as destruction of wetlands or drainage, are unlikely to lead to significant or predictable changes in the frequency of large floods. This is because the changes tend to be modest in relation to the overall size of the basin. As well, during a large flood, the natural hydrometeorological conditions tend to overwhelm anthropogenic effects. Nevertheless, research into the effects of land-use change on smaller floods, particularly in sub-basins, would be useful.

Knowledge and Program Needs

Floodplain Mapping

The reality of floodplain management is that unless a flood actually occurs, the threat of flooding often falls out of the public consciousness. Improvements in statistical approaches, GIS and mapping technologies, and improved simulation models highlight the need for a review of past mitigation and adaptation strategies. There is a need to re-examine standard accepted engineering approaches to mitigation in the context of these advancements.

Potential improvements in determining regulatory floods include a number of approaches such as regional analysis that must be considered in addition to improving conventional single-station, flood-frequency analysis. Flood-frequency analysis based on the historic record of annual peak floods is also a fundamental tool in determining design discharge for floodplain zoning, flood protection infrastructure, and structures that span rivers. A basic assumption in frequency analysis is that climatic trends or cycles do not affect flood flows, but there is clear evidence that this is not the case (Gosnold et al., 2000), and that even modest changes in climate can result in large changes in flood magnitude (Knox, 1993). Climate change impacts in terms of precipitation should also be examined, including updated intensity-duration-frequency precipitation curves, which are vital to proper urban engineering design.

With the advent of remote-sensing techniques, in particular LIDAR and GPS, in combination with GIS, weather radar, and the improving ability of NWP models to forecast, now-cast and hind-cast precipitation, it is time to re-think flood mapping and forecasting mitigation strategies. Hydrological and hydraulic models applied in conjunction with atmospheric models in a probabilistic framework may provide a viable mechanism to examine potential future climate change scenarios in the context of floodplain mapping. These improved statistical and regional analyses of floods within a climate change context also should be examined.

Forecasting and Models

Mathematical models play an increasingly important role in flood mitigation and forecasting. There are two trends, however, that call for the application of significant research effort. First, the increasing availability of remotely sensed data, such as precipitation, snow water equivalent or evapotranspiration, requires modification of models to accept spatially distributed as well as more traditional point data. Improvements to the algorithms for transforming data to useful information, such as improved data assimilation algorithms using combinations of observed and modelled data, are vital to improvements in modelled precipitation – and consequently to hydrological forecasts. Clearly, continued improvements to operational weather models are also required.

The hydrological community needs to focus on hydrological modelling systems that are consistent with atmospheric modelling practice. As such, research into physically based distributed models that can be linked or coupled with atmospheric models should be highly encouraged. These models should be based on existing atmospheric land-surface schemes, and provide the link between the atmosphere and the land surface, simulating both the water and energy balance at the land surface. Physically based hydrological models allow for a more rigorous examination of discrete hydrological processes such as precipitation, interception, infiltration, interflow, and baseflow (Soulis et al., 2000). Such models could be used to examine, for example, anthropogenic impacts on a watershed. Issues such as effects of conversion of a land surface to agricultural purposes, e.g., drainage development or wetland destruction, on runoff volumes and peaks generate considerable public debate. These models should be developed by the hydrological community, and based on continued process and basin-scale experiments. Given the diversity of landscapes, and the heterogeneity of the land surface, continued improvements in hydrological models require an effective synergy between experimentalists and model developers in hydrology.

Data Needs

- Accurate atmospheric forcing and hydrological information is essential for hydrological modelling and infrastructure design, particularly with the advent of climate change. A more consistent hydrometeorological approach to network design should be established. Streamflow gauges are integrators of atmospheric forcing, and the network in Canada should reflect this reality.
- Techniques to make effective use of ground-based radar estimates of precipitation are essential for improved design and mitigation.
- Cryospheric datasets of variables, in particular SWE and snow cover extent provide vital information for flood forecasters. There is no systematic system for estimating these quantities, and currently no established archive of these data.
- Current technology allows for establishment of *in situ* soil moisture monitoring stations. These types of data could be established within the existing infrastructure and are vital input into data assimilation methods.
- An ongoing research effort is required to develop reliable remotely sensed methods for monitoring soil moisture, SWE and other important state variables over different land-cover and terrain types in Canada.

- Accurate, high resolution DEMs are needed for a variety of modelling applications.
- Potential users need to be aware of NWP output products that can benefit the operational flood-forecasting community (e.g., distributed forecasts of local runoff or soil moisture), and could also be archived and made available to the engineering-design community. Data-assimilated variables from the NWP provide our best estimate of the state of the atmosphere and the land surface, and represent, where possible, a blending of model and observed data.

Research Needs

- Currently the technology used in operational forecasting models lags the research models by 10 to 20 years, although some have been upgraded to include new data sources. There is a need to test newer and more comprehensive models in operational settings. The major difference between these applications is in the implementation and use of spatial data, both from a meteorological forcing aspect (this includes data-assimilated meteorological inputs in real time, remote sensing state variables) and from a physiographic input perspective (e.g., digital elevation models, satellite-derived land-cover information).
- Flood frequency analysis based on the historic record of annual peak floods is also a fundamental tool in determining the design discharge for floodplain zoning, flood protection infrastructure, and structures that span rivers. Frequency analysis requires an assumption of stationarity so that climatic trends or cycles do not affect flood flows, but there is clear evidence that this is not the case (Gosnold et al., 2000), and that even modest changes in climate can result in large changes in flood magnitude (Knox, 1993). A research challenge is to determine how aspects of climate change can be incorporated into flood frequency analysis for planning purposes.
- The use of weather models coupled with hydrological models may provide one of the only avenues to explore future scenarios for adaptation and mitigation. Furthermore, the basic assumptions of homogeneity and independence of any time series of flood peaks can easily be called into question, particularly when evaluating the relatively short Canadian climate and hydrometric records (Booy and Morgan, 1985; Klemes, 1987; Watt, 1989). Potential improvements in the determination of regulatory floods include a number of approaches, such as regional analysis, that must be considered in addition to improving conventional single-station, flood-frequency analysis.
- The method of calculating the PMF or other design storms should be examined, particularly under the pretext of climate change. Design storms derived from historic data (e.g., Intensity-Duration-Frequency curves, 100-year flow estimates) may have changed substantially for certain regions of the country. There is an important need to re-assess these design criteria from a deterministic modelling and statistical approach.
- Erosive thresholds are most likely to be crossed during severe floods along rivers where the channel planform is close to the meandering-braid transition. A better understanding of the erosive threshold would allow river reaches that are susceptible to large-scale erosion, during extreme floods, to be recognized, and assessments to be made of the vulnerability of valley bottom development and infrastructure to large-scale erosion.

References

Abbs, D.J. 1999. A numerical modeling study to investigate the assumptions used in the calculation of probable maximum precipitation. Water Resour. Res. 35(3): 785-796.

Andrews, J. (ed.). 1993. Flooding: Canada water year book. Ministry of Supply and Services, Ottawa.

Benoit, R., M. Desgagné, P. Pellerin, S. Pellerin, Y. Chartier and S. Desjardins. 1997. The Canadian MC2: a semi-Lagrangian, semi-implicit wideband atmospheric model suited for finescale process studies and simulation. Monthly Weather Review 125: 2382-2415.

Booy, C. and D.R. Morgan. 1985. The effect of clustering of flood peaks on a flood risk analysis for the Red River. Can. J. Civil Eng. 12: 150-165.

Brooks, G.R., S.G. Evans and J.J. Clague. 2001. Flooding, p. 101-143. *In* G.R. Brooks (ed.), A synthesis of natural geological hazards in Canada. Geological Survey of Canada Bulletin 548. Ottawa.

Burn, D.H. 1990. Evaluation of regional flood frequency analysis with a region of influence approach. Water Resour. Res. 26: 2257-2265.

Burn, D.H. 2002. Hydrological extremes, p. 1017-1021. *In* El-Shaarawi, A. and W. Piegorsch (ed.), Encyclopedia of environmetrics, Volume 2. John Wiley & Sons, Ltd., Chichester.

Canadian Dam Association. 1998. Dam safety guidelines. Edmonton, Alberta.

Commission scientifique et technique sur la gestion des barrages. 1997. Report, The scientific and technical committee on the management of dams in Quebec. Canadian Dam Safety Association, Quebec.

Côté, J., S. Gravel, A. Méthot, A. Patoine, M. Roch and A. Staniforth. 1998. The operational CMC-MRB global environmental multiscale (GEM) model. Part I: design considerations and formulation and Part II: results. Monthly Weather Review 126: 1373-1418.

Federal Energy Regulatory Commission. 2002. Engineering guidelines for the evaluation of hydropower projects. Washington, D.C. 644 p. Available from: http://www.ferc.gov/industries/hydropower/safety/eng-guide.asp; Internet. Cited 2 October 2003.

Gosnold, W.D., J.A. LeFever, P.E. Todhunter and L.F. Osbourne Jr. 2000. Rethinking flood prediction: does the traditional approach need to change? Geotimes 45: 20-23.

IH (Institute of Hydrology). 1999. Flood Estimation Handbook. Centre for Ecology and Hydrology Wallingford. Wallingford, U.K.

IJC. 2000. Living with the red. A Report to the Governments of Canada and the United States on Reducing Flood Impacts in the Red River Basin. International Joint Commission, Ottawa and Washington.

Jarrett, R.D. and E.M. Tomlinson. 2000. Regional interdisciplinary paleoflood approach to assess extreme flood potential. Water Resour. Res. 36(10): 2957-2984.

Klemes, V. 1987. Hydrological and engineering relevance of flood frequency analysis. *In* V.P. Singh (ed.), Hydrologic frequency modelling. Kluwer Academic Publishers.

Knox, J.C. 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361: 430-432.

Kouwen, N. and R. Benoît. 2002. Regional forecasting of river flows using a high resolution numerical weather model coupled to a hydrological model. *In* Proceedings, International conference on flood estimation, Bern, Switzerland, March 6-8, 2002.

Kulshreshtha, S. 2003. Personal communication.

Lin, C.A., L. Wen, M. Béland and D. Chaumont. 2002. A coupled atmospheric-hydrological modeling study of the 1996 Ha! Ha! River basin flash flood in Quebec, Canada. Geophys. Res. Lett. 29(2): 13/1-13/4.

Mailhot, J., S. Bélair, R. Benoît, B. Bilodeau, Y. Delage, L. Fillion, L. Garand, C. Girard and A. Tremblay. 1998. Scientific description of RPN physics library, Version 3.6. Recherche en Prévision Numérique, Atmospheric Environment Service, Dorval, Québec. Available from: http://www.cmc.ec.gc.ca/rpn; Internet. Cited 2 October 2003.

Parrett, C. and R.D. Jarrett. 2000. Flood hydrology for Dry Creek, Lake County, Northwestern Montana, p. 4.13.1-4.13.10. *In* Hotchkiss, R.H. and M. Glade (ed.), Proceedings, building partnerships: joint conference on water resources engineering and water resources planning & management. ASCE.

Pietroniro, A. and E.D. Soulis. 2003. A hydrology modelling framework for the Mackenzie GEWEX Program. Hydrolog. Process. 17: 673-676.

Pietroniro, A., E.D. Soulis, K. Snelgrove and N. Kouwen. 2001. A framework for coupling atmospheric and hydrological models. *In* Dolman, A.J., A.J. Hall, M.L. Kavvas, T. Oki and J.W. Pomeroy (ed.), Soil-vegetation-atmosphere transfer schemes and large scale hydrological models. IAHS Publication No. 270.

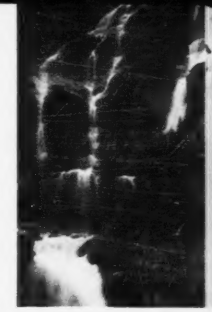
Prowse, T. and M. Conly. 1996. Impacts of flow regulation on the aquatic ecosystem of the Peace and Slave rivers. Northern River Basins Study Synthesis Report No. 1.

Shrubsole, D., G. Brooks, R. Halliday, E. Haque, A. Kumar, J. Lacroix, H. Rasid, J. Rousselle and S.P. Simonovic. 2003. An assessment of flood risk management in Canada. ICLR Research Paper Series - No. 28. Institute for Catastrophic loss Reduction. University of Western Ontario

Soulis, E.D., K.R. Snelgrove, N. Kouwen, F. Seglenieks and D.L. Verseghy. 2000. Towards closing the vertical water balance in Canadian atmospheric models: coupling of the land surface scheme CLASS with the distributed hydrological model WATFLOOD. Atmosphere-Ocean 38(1): 251-269.

Watt, W.E. (ed.). 1989. Hydrology of floods in Canada: a guide to planning and design. Associate Committee on Hydrology, National Research Council, Ottawa.

World Meteorological Organization. 1986. Manual for estimation of probable maximum precipitation. Operational Hydrology Report No. 1, WMO No. 332, Geneva, Switzerland.



Chapter 5

MUNICIPAL WATER SUPPLY AND URBAN DEVELOPMENT

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Current Status

Urban development interferes with water resources by altering the hydrological cycle and increasing demands on provision of water services in the affected areas. Changes in the hydrological cycle include altered fluxes of water, sediment, chemicals and microorganisms, and increased releases of waste heat. In general, such changes lead to flow and sediment regime changes, geomorphological changes, impaired water quality, reduced biodiversity and overall degradation of water resources. At the same time, growing urban populations impose increasing demands on provision of water services, including water supply, drainage, wastewater collection and management, and beneficial uses of receiving waters. Integrated urban water management is used to mitigate the conflicts between urban development demands on water services and the resulting impacts on local water resources. Specific aspects of urban development impacts on receiving waters and threats to water availability for municipal water supply are addressed in this chapter. Even though the emphasis was placed on water quantity and availability issues, certain aspects of water quality are also included where appropriate.

Impacts of Urban Development on Water Resources

The discussion of urban development impacts on water resources begins with impacts on water quantity, followed by those on water quality.

Compared to natural watersheds, the hydrological cycle in urban areas is significantly altered and changes may occur in the atmospheric phase, e.g., local meteorological phenomena and microclimate leading, for example, to increased precipitation downwind of cities, higher incidence of fog, and higher air temperatures.

Changes in the land phase include increased volumes and discharges of surface runoff which contribute to flooding or water ponding (see also Chapter 4). There are related increases in soil erosion; changes in the sediment regime relating to sediment transport and deposition (siltation) and stream geomorphology; reduced evapotranspiration; reduced infiltration; groundwater pollution; thermal enhancement of receiving waters; densimetric stratification; and impacts on wetlands through drainage and pollution.

Groundwater recharge may decrease due to increased imperviousness, but such recharge losses may be partly offset by leakage from water pipes and sewers, and intentional infiltration of roof runoff or stormwater practised in some urban areas. The group *American Rivers* recently reported losses in groundwater recharge due to urban sprawl and increased catchment imperviousness: for the urban areas developing most rapidly during the period from 1982 to 1997 (e.g., Atlanta, Ga.), simple estimates of recharge reductions ranged from 200 to 500 million m^3/year (American Rivers, 2002). Qualitatively similar findings would be found in fast growing Canadian urban areas.

Demands on water services lead to increased withdrawals from source waters, which may affect other receiving water uses relating to source apportionment, low and high flows, stream habitat and ecology, and groundwater levels. Return of flow/filter backwash and treatment plant residuals may contribute to water pollution. With respect to the collection and management of wastewaters, effluent disposal to receiving waters may cause pollution and affect the flow regime. Leaky sanitary/combined sewers may contribute to groundwater pollution.

Fundamental water regime changes caused by urban development affect instream water uses, such as recreation (swimming, boating, and fishing); operation of multipurpose reservoirs, with conflicting demands of water supply, recreation, hydropower generation and flood protection imposed on reservoir operation; and, aesthetic and ecological functions of receiving waters.

Specific impacts of urban runoff (stormwater) on water quality and ecosystem health were addressed earlier in a companion report titled *Threats to Sources of Drinking Water and Aquatic Ecosystem Health in Canada* (Environment Canada, 2001) and are briefly summarized below.

Discharges of urban stormwater cause physical, chemical, microbiological and combined impacts on water quality.

Physical impacts include:

- increased flow (the effects of which are flooding, erosion, habitat washout)
- changes in sediment regime (habitat destruction, interference with water quality processes, impacts on aquatic life, transport of contaminants)
- thermal energy inputs (thermal pollution, loss of cold water fisheries), and
- densimetric stratification (impairment of vertical mixing and oxygenation of bottom water layers) (Marsalek et al., 2001).

Chemicals discharged with stormwater include:

- biodegradable organics (contribute to dissolved oxygen depletion), nutrients (eutrophication), and
- trace metals, chloride, persistent organic pollutants (POPs) and hydrocarbons (acute and chronic toxicity, and genotoxicity).

Microorganisms conveyed by stormwater include bacteria and viruses of fecal origin and their discharges contribute to beach closures and contamination of shellfish harvesting areas. Typically, combinations of physical, chemical and microbiological impacts are encountered in receiving waters and are measured by the performance of biological communities (Marsalek et al., 2001).

Discharges of municipal wastewater treatment plant effluents cause chemical, microbiological and combined impacts on receiving waters. The chemicals of concern in these effluents include:

- conventional constituents (suspended solids, chemicals causing biochemical and chemical oxygen demand, nutrients)
- toxicants (chlorine, ammonium, trace organics, trace metals), and
- new chemicals of concern (endocrine disrupters, pharmaceutical and therapeutic products, antibiotics).

Microorganisms in the effluents include indicator bacteria, viruses, helminths and protozoa. The main impacts of municipal wastewater treatment effluent discharges include restrictions on fish and shellfish consumption, degradation of aquatic and wildlife populations and their habitat (including water and bottom sediment quality), eutrophication or undesirable algal growth, isolated incidents of waterborne diseases caused by sewage contamination of drinking water supplies, beach closures, degradation of aesthetics, and added costs to agricultural, industrial, and municipal users for treatment of water (Chambers et al., 1997).

Municipal wastewater effluent discharges may adversely affect the aquatic ecosystem by alterations of chemical dynamics, energy dynamics, food web (trophic dynamics), dispersal and migration, disturbance of ecosystem development, reduced biodiversity, loss of critical species, and reduced genetic diversity (Lijklema et al., 1993).

Threats to Municipal Water Supply

On a national basis, Canada has abundant sources of water and has been ranked second best in the world (after Finland) in a recent international survey of the *Water Poverty Index* (Sullivan, 2002). This index takes into consideration water resource (internal flows, external inflows, population), access (percentage of population served by water supply and sanitation, access to irrigation water), use (domestic, industrial and agricultural uses), capacity (the level of human and financial capacity to manage the system), and environment (indicator of ecological integrity, or adequacy of water resources for environmental needs). In spite of this favourable assessment of Canadian water resources, some communities in Canada have been experiencing water supply shortages, which are caused by water quantity and/or water quality problems. About 26% of municipalities with water supply systems reported water shortages during the 1994 to 1999 period, for such reasons as seasonal shortages due to droughts, infrastructure problems, and increased consumption. In a water use survey published by Environment Canada (2002b), municipalities dependent on municipal groundwater systems reported water shortages more frequently than did those relying on surface waters. Regional experience may differ from these national survey findings.

Municipal Water Use: The discussion of threats to municipal water supply begins with municipal use, followed by the issues related to the sources, treatment and distribution infrastructure. This sequence follows the multi-barrier approach to drinking water protection and is maintained throughout the whole chapter.

Municipal water use includes all water supplied by the municipal water system. It is categorized by Environment Canada (2002a) as residential, commercial, industrial and "other." "Other" includes water lost through leakage; unaccounted-for-water uses, such as fire fighting or distribution system flushing; and, water that the municipality was unable to assign to one of the first three categories. The best indicators of water use in urban areas are municipal water use of 638 litres/capita/day (the 1999 national average for all municipal sectors) and residential water use of 343 litres/capita/day. The latter use accounts for more than half of all municipal water use in Canada and ranges from 240 to 460 litres/capita/day; much

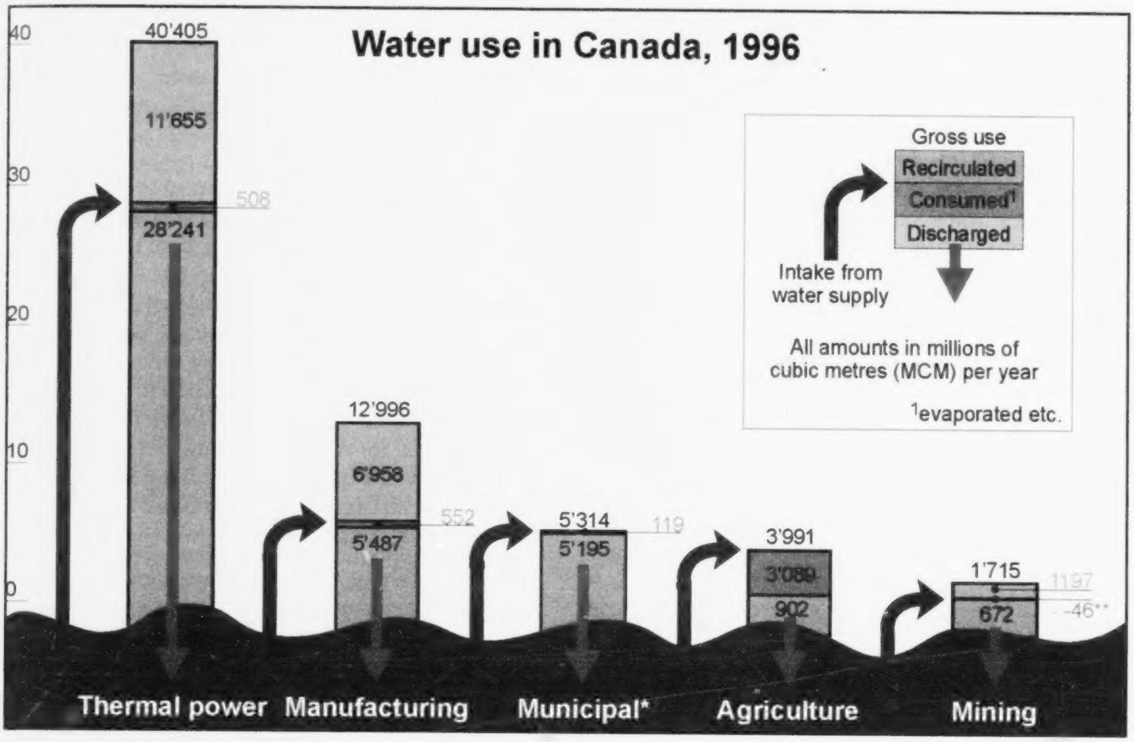


Fig. 1. 1996 water use in Canada (Environment Canada, 2002b).

lower values can be found in northern Canada (Environment Canada, 2002a,c).

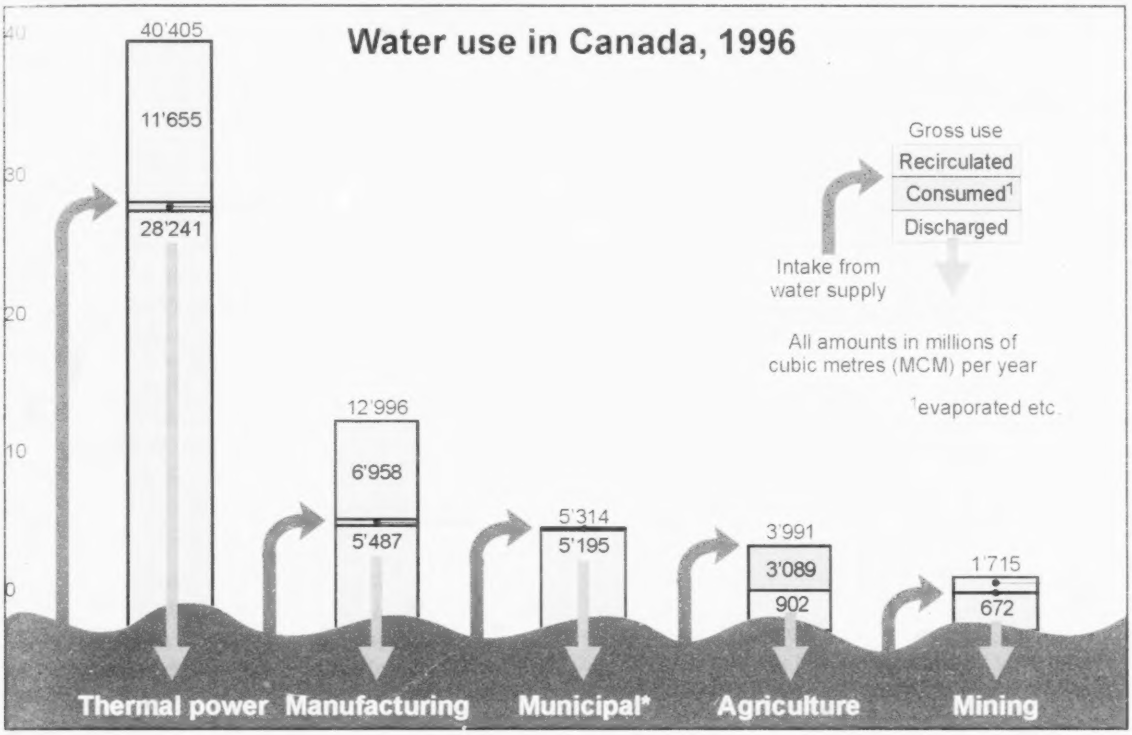
According to the Organisation for Economic Cooperation and Development (OECD, 1999), Canada is among the largest per capita users of residential water among the developed nations and is in a group including the United States, Australia and Japan. It is important to note (Fig. 1) that municipal water use represents only 11% of all water use (withdrawals) in Canada, other major user sectors being agriculture, mining, manufacturing and thermal power generation.

Municipal Water Supply Sources: Selection of water supply source is based on such considerations as safe yield, water quality, collection requirements (intakes, wells), treatment requirements (including residue disposal), and transmission/distribution (Hamann et al., 1990). Both surface water bodies and aquifers are used to supply water to urban residents. Approximately 74% of Canadians use surface water and 26% use groundwater for water supply (Environment Canada, 2002b). For both surface waters and aquifers, sustainable withdrawals can be determined based on either lake levels, and/or stream levels, water table levels, streamflows, and water apportionment. Source water limitations force suppliers to access less desirable sources, e.g., in the Prairies, deeper wells that may have highly mineralized water.

For surface sources, this may require the use of more distant sources, or development of sources with lower water quality requiring more complex treatment entailing more losses in the treatment process. Stress on both surface water and groundwater sources may lead to service disruptions, which can often be mitigated by proactive demand side management (advisory bulletins, restrictions, pricing). New, but so far relatively minor, sources include (a) subpotable water obtained by wastewater and greywater reclamation and/or recycling, (b) rainwater, and (c) bottled drinking water.

Water Treatment Systems: Water treatment systems are required to make raw water drinkable. As high quality sources of water become depleted, municipalities are increasingly using lower quality source water requiring more treatment. However, depending on the causes of lower source water quality, this approach may increase human health risk in drinking water supply by increased reliance on technology and safe operation in drinking water supply. Equipment and/or operator failures may lead to serious consequences (O'Connor, 2002).

Another shortcoming of using lower quality source water arises because more complex treatment systems tend to consume more water in the treatment process, mostly in the form of wastewater and sludge produced in various treatment processes. The choice of the water treatment processes depends on: source quality, required finished water quality, reliability of process equipment, operational requirements, and staff qualifications and training. It must take into account chang-



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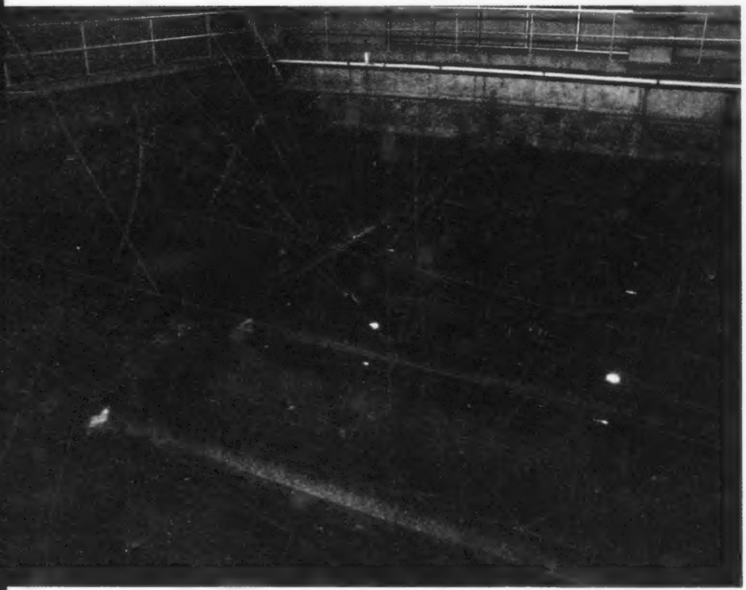
Typical treatment schemes for surface water and groundwater differ. Water quality problems associated with surface water quality include particulate levels, colour, taste and odour, and microbiological content. The treatment processes commonly applied include coagulation, flocculation, and sedimentation, followed by filtration and disinfection (Hamann et al., 1990). In groundwater, the main water quality problems include high hardness, iron and manganese contents. Treatment schemes may include lime or soda ash treatment, flocculation, filtration and disinfection.

Water Distribution Systems: Water distribution includes the entire infrastructure from the source water treatment outlet to the tap. On average, about 20% of total daily municipal water use is attributed mostly to distribution losses and also to unaccounted-for-water. It is further recognized that reported values of losses are generally underestimated and increase with the age of the distribution system. Many Canadian municipalities address the issue of losses, but to a varying extent ranging from reactive repairs to proactive loss management programs. A necessary component of unaccounted-for-water is that required by various operational measures including the flushing of pipes and reservoirs to maintain water quality in the distribution network. Focus on security of water reservoirs and distribution networks, in relation to protection against various threats and accidents, has increased substantially since 2001 (U.S. EPA, 2002).



Backwashing sand filters in a water treatment plant.

Trends and Emerging Issues

Trends

Trends in municipal water use, distribution, treatment and sources are discussed below.

Municipal water use has been affected by steady population growth in Canadian urban areas, due to overall population increase and migration from rural to urban areas. Statistics Canada (2002) indicates that the total urban population in Canada increased from 22.5 million in 1996 to 23.9 million in 2001, reaching 77.9% of the total population. Thus, the water supply services have been growing to service this population and also in response to the pressure from public health authorities requiring municipalities to connect existing developments to municipal water supply systems. The premise for this action is that managing small, distributed water systems is more difficult and may involve greater safety risks.

Since 1989, the national average values of per capita use have fluctuated from year to year, but without any significant changes. There is a trend towards metered water supply: the total number of Canadians with metered water increased from 52% in 1991 to 57% in 1999 (Environment Canada, 2002b). Finally, there is a trend towards demand management by means of (a) economic instruments (full-cost recovery), (b) structural and operational measures (metering, waste detection, low-flow devices, and reduced pressure), and (c) socio-political instruments. While this trend is hard to assess quantitatively, increasing moves towards full-cost pricing and more widespread community restrictions on watering provide indirect evidence of increasing demand management.

Several trends can be detected relating to water distribution systems. In general, distribution systems are ageing and funding for recapitalization is scarce. There is a move towards management of distribution systems for performance, including leak detection, minimization of losses, and management of water quality (e.g., rechlorination to maintain chlorine residual and control biofilm growth). Gradually, distribution infrastructure is being upgraded to meet new seismic, safety, and security standards.

Trends in water treatment systems indicate continuous upgrading, reflecting higher standards for finished water and higher consumer expectations. Such upgrading then leads to higher costs of water supply and greater use of water during the actual treatment process. At the same time, improvements in technology allow treatment of poorer quality water and thereby open up new sources. The use of lower quality source water, with more treatment, needs to be considered within the framework of the multi-barrier approach to risk management of drinking water.

Trends in municipal water sources include improved protection of sources and development of new minor sources. The protection of sources is a challenge in many locations. Threats to or limitations on sources are imposed by increased instream uses, toxic spills, security risks, and demands on water export. Increased instream uses and/or toxic spills restrict municipal sources and force suppliers to look for new sources, often more distant and/or with lower water quality. The development of such sources increases the costs of water supply. Similarly, improvements in security of sources and distribution infrastructure also add to cost of water.

Bulk water removal from Canadian catchments is opposed by the federal government and many provinces have in place, or are developing, legislation or regulations prohibiting bulk water removal. Finally, the recent Walkerton and North Battleford inquiries drew attention to drinking water safety in Canada and the need to apply the multi-barrier approach to prevent contamination of drinking water (O'Connor, 2002). This increasing awareness of source water protection is leading to implementation of specific protection measures and more comprehensive water supply planning.

There is a trend towards developing/enhancing some new, but so far minor, sources of water. In particular, use of bottled water is increasing (supplied in both regular bottles and large containers). Wastewater reclamation and recycling and reuse for sub-potable water supply are also increasing, for wastewater (municipal and industrial), greywater, stormwater and rainwater. Typical uses include landscape and agricultural irrigation, fire protection, urban waterscape, in-building uses, recreational waters, and industrial reuse. Reclaimed or recycled water substitutes for potable quality water and thereby creates reserves for potable water supply.

Finally, there is increasing participation of the private sector in water supply services in Canada. Frequently cited advantages include possible efficiency gains, technological innovation, and enhanced ability to raise capital funds. Disadvantages include the perception that private ownership of water sources and/or supply systems may lead to inequities in service, restricted availability to the economically disadvantaged, and loss of public control (Lee et al., 2001; Lundqvist et al., 2001).

Emerging Issues

A number of emerging issues can be identified in municipal water use, treatment, and source protection.

As the cost of water increases and the portion of delivered water being metered increases, it is expected that consumption will decline. In general, higher water quality, infrastructure renewal, increased security, and full-cost recovery justify price increases. There are various definitions of full-cost pricing, but most commonly, it includes capital costs, operation and maintenance costs, including depreciation allowances. There is an increasing awareness of "virtual" water (e.g., water incorporated in products, such as canned or processed foods), which represents a water use competing with other uses in urban areas. Historically, groundwater supplies did not require disinfection. However, disinfection of groundwater may now be required.

Recharging aquifers and storing water for peak demand may enhance water sources. It is expected that climate change will affect water sources, particularly in southern Canada. Predicted effects include reduced flows and levels in rivers and lakes, declining groundwater levels, and higher water temperatures. Significant changes are predicted regarding water storage in glaciers and snow, with expected strong impacts on water supply. Generally, lower quality source water is expected, with higher suspended solids (resulting from more frequent severe storms), increased water use with higher air temperatures, and impacts on water distribution (for higher water temperatures, there is a potential regrowth of bacteria). Public awareness of potential future shortages should lead to more efficient water use.

Finally, two socio-political issues have also been identified. Globalization affects water supply, both favourably, as regards new technology and increased trade, and unfavourably, by creating pressure to export Canadian water. Water can no longer be viewed just as a commodity and the Canadian public increasingly recognizes the ethical dimension of water supply.

Knowledge and Information Needs

The following bullets encapsulate knowledge and information requirements. These span the breadth of the municipal water supply, with respect to water use, distribution, treatment, and sources.

Municipal Water Use

- Enhance public awareness of the need to use water more efficiently and reduce water consumption.
- Demand side management – there is a need to produce a searchable database of best practices, water-saving (wise-use) devices, regulatory/economic/social instruments to influence the uptake of these practices by urban residents, in support of sustainability. An example of such a program for Barrie, Ontario, can be found on the U.S. EPA web site (http://www.epa.gov/OW-OWM.html/water-efficiency/utilityconservation.pdf).
- Develop a better understanding of various water uses (essential and non-essential, and associated environmental impacts) and the forces driving use patterns.
- Collect water use data in temporal and spatial detail sufficient to detect sectoral use, losses and unaccounted-for-water, regional variations, and trends.
- Collect data on effects of weather/season on water use.

Water Distribution Systems

- Develop a better knowledge of demand variation, regarding peak and base uses.
- Undertake an inventory of the condition/capacity of the existing distribution and treatment systems.
- Develop institutional arrangements/policies/financial approaches ensuring a timely replacement of the ageing water supply infrastructure.

Water Treatment Systems

- Address the issue of potential presence of new chemicals of concern (endocrine disrupters, pharmaceuticals, and therapeutics) in source water and their removal by treatment.
- Develop new processes for reclamation and/or recycling of wastewater, greywater, rainwater, stormwater and process waters.

Municipal Water Supply Sources

- Develop integrated water management plans, which would ensure the protection of drinking water sources. New legislation may be needed to remove impediments to the development and implementation of such plans.

References

American Rivers. 2002. Paving our way to water shortages: how sprawl aggravates drought. Available from: www.amrivers.org; Internet. Cited 14 August 1003.

Chambers, P.A., M. Allard, S.L. Walker, J. Marsalek, J. Lawrence, M. Servos, J. Busnarda, K.S. Munger, K. Adare, C. Jefferson, R.A. Kent and M.P. Wong. 1997. Impacts of municipal wastewater effluents on Canadian waters: a review. Water Qual. Res. J. Canada 32: 659-713.

Environment Canada. 2001. Threats to sources of drinking water and aquatic ecosystem health in Canada. National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 1.

Environment Canada. 2002a. Economic and Regulatory Affairs. Municipal water pricing 1991-1999. Available from: http://www.ec.gc.ca/erad/dwnld/waterreportbw.pdf; Internet. Cited 14 August 2003.

Environment Canada. 2002b. Urban Water Indicators: Municipal Water Use and Wastewater Treatment. Available from: http://www.ec.gc.ca/soer-ree/English/Indicators/Issues/Urb_H2O/; Internet. Cited 6 November 2003.

Environment Canada. 2002c. Freshwater Website. The Management of Water. Water Use. Available from: http://www.ec.gc.ca/water/en/manage/use/e_use.htm; Internet. Cited 6 November 2003.

Hamann, C.L., J.B. McEwen and A.G. Myers. 1990. Guide to selection of water treatment processes, p. 157-187. *In* F.W. Pontius (ed.), Water quality and treatment. AWWA, McGraw-Hill, Inc., Toronto.

Lee, T., J.-L. Oliver, P.-F. Teniere-Buchot, L. Travers and F. Valiron. 2001. Economic and financial aspects, p. 313-343, chapter 7. *In* C. Maksimovic and J.A. Tejada-Guibert (ed.), Frontiers in urban water management: deadlock or hope? IWA Publishing, London, UK.

Lijklema, L., J.M. Tyson and A. Lesouf. 1993. Interactions between sewers, treatment plants and receiving waters in urban areas: a summary of the INTERURBA '92 workshop conclusions. Water Sci. Technol. 27(12): 1-29.

Lundqvist, J., S. Narain and A. Turton. 2001. Social, institutional and regulatory issues, p. 344-398, chapter 8. *In* C. Maksimovic and J.A. Tejada-Guibert (ed.), Frontiers in urban water management: deadlock or hope? IWA Publishing, London, UK.

Marsalek, J., M. Diamond, S. Kok and W.E. Watt. 2001. Urban runoff, p. 47-50, chapter 11. *In* Threats to sources of drinking water and aquatic ecosystem health in Canada. Environment Canada, National Water Research Institute, Burlington, Ontario. NWRI Scientific Assessment Report Series No. 1.

O'Connor, D. 2002. Part two. Report of the Walkerton Inquiry. A strategy for safe water. Available from: http://www.attorneygeneral.jus.gov.on.ca/english/about/pubs/walkerton/part2/; Internet. Cited 14 August 2003.

OECD. 1999. The price of water: trends in OECD countries. OECD, Paris.

Statistics Canada. 2002. 2001 Census: Standard data products: Population and Dwelling Counts: Urban and Rural. Available from: http://www12.statcan.ca/english/ census01/products/standard/popdwell/Table-UR-PS.cfm; Internet. Cited 14 August 2003.

Sullivan, C. 2002. Calculating a water poverty index. World Development 30(7): 1195-1210.

U.S. EPA. 2002. Water infrastructure security. Available from: http://www.epa.gov/safewater/security/; Internet. Cited 14 August 2003.

Chapter 6

MANUFACTURING AND THERMAL ENERGY DEMANDS

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Current Status

Water is important to the manufacturing process. Without water to use in processing, to serve in cooling, condensing and steam generation, and to convey waste material, industry would be unable to function; consequently, as in many industrialized countries, manufacturers in Canada use large quantities of this resource. In terms of total withdrawals, thermal power generation dominates, extracting some 28,750 million cubic metres (MCM) per year in 1996 – the last year for which national estimates are available (Environment Canada, 2002). Canadian manufacturing industries are next, withdrawing just over 6000 MCM/year in 1996 (Environment Canada, 2002). In comparison, withdrawals in other sectors totalled 5100 MCM/year (municipal), 4000 MCM/year (agriculture), and 364 MCM/year (mining) in 1991 (Statistics Canada, 2000). This chapter deals with water quantity issues in Canada's manufacturing and thermal power (principally nuclear and coal) sectors; mining, including the oil industry, and the hydroelectric sectors are covered in other chapters.

With such large withdrawal rates, Canadian manufacturing can have a significant impact on water availability, particularly with competing instream and other consumptive uses. Some manufacturing sectors, chiefly the pulp and paper, chemical and metallurgical industries, use large amounts of freshwater, and consequently must dispose of significant amounts of waste. These wastewaters are often released into some of Canada's most important rivers and lakes, in terms of ecological habitats and other human uses, and can cause significant environmental degradation and restrictions in water availability for downstream users.

Interestingly, manufacturing plants can often be both the primary cause and the injured party of water quantity depletion. Depletion has led, for example, to increased costs of industrial water acquisition, in addition to the need to develop new public water supplies. As part of a reliability study of the Metropolitan Water District in California, researchers estimated the cost of water shortages to users. They reported: "It has been estimated that a 15% shortage to the water sensitive industries in Southern California could cause about $3.5 to $4.0 billion in lost jobs and production" (Rodrigo et al., 1996).

Manufacturing Water Use[1]

Water Intake: Nationally, total water withdrawals have been on the decrease since 1981. Paper and allied products, primary metals, chemicals and chemical products industries made up 82% of total water intake in 1996 (Table 1). Ontario accounted for one-half of the total Canadian manufacturing water intake in 1996, followed by Quebec and British Columbia.

Water Intake Relative to Output: For the last two decades, water intake has fallen relative to real manufacturing output. This is most likely a function of changing environmental regulations, technological change and/or changes in other input prices. For example, water quality legislation has curtailed industrial water emissions and, thus, water intake. Similarly, firms' efforts to conserve energy and raw materials have in some cases led to reductions in water intake (Renzetti, 2003). It is likely not a function of water price increases since most manufacturing use is self-supplied.

Water Sources: The manufacturing sector obtains 82% of its water supply from self-supplied freshwater surface sources, roughly unchanged from 1991. The remaining 18% comes from public utilities (9%), groundwater (3%), other freshwater (3%), and brackish water (mainly tidewater) (3%). Industry groups dominated by relatively small establishments tend to draw a larger proportion of their water supplies from public utilities, while larger industries (e.g., paper and allied products, primary metals, chemicals and chemical products, petroleum and coal products) withdraw water supplies mostly from private freshwater sources.

Purpose of Water Use: On the whole, manufacturers use 49% of the total intake for process water and 47% for cooling, condensing and steam generation, although there are deviations from this in many sectors (e.g., process water makes up over 75% of that withdrawn by the paper and allied products sector). Sanitary uses make up a very small percentage (2%) of total intake.

Water Reuse: Although reuse rates vary significantly among industrial sectors, on the whole, water reuse rates are up modestly from 1991, reversing the trend from 1986 and 1991 when reuse rates were on the decline. Reuse rates are highest in the plastics, transportation equipment, petroleum and coal, paper and allied products, chemicals and chemical products, rubber and primary metals industries. Lowest reuse rates are in the wood products, beverage, fabricated metals, food and textile products sectors (Table 1). The recent trend toward increased water reuse in general is a positive development, although difficult to explain. As stated above, environmental regulations, technological change and/or changes in other input prices are likely the key influences, and these will be sector, and in many cases, facility specific in nature. Consequently, estimating future reuse trends is problematic.

Wastewater Discharge: Total wastewater discharge is down from 1991, 70% of which is discharged to private surface waters. 16% is discharged to tidewater, 14% to public sewers; and less than 1% to groundwater.

Water Consumption (intake-discharge: refers here to water that is not returned to its original source: i.e., escaped steam or water incorporated into a final product): Nationally, water consumption was 9% of total withdrawals in 1996, up from 7% in 1991. The beverage, wood products, and transportation equipment sectors have the highest rates of consumption (Table 1). In general, water use and consumption rates in the Atlantic Provinces were among the lowest in Canada, a function of water availability and industrial make-up. Use rates for the Prairie Provinces (Saskatchewan and Alberta particularly) were substantially higher than those in the rest of Canada. This reflects the need for greater water recirculation by plants, due largely to a semi-arid climate that requires enhanced water conservation efforts.

Table 1. Selected characteristics of manufacturing and thermal energy water use (MCM water/year), by parameter and industry group, 1996

Industry Group	Intake	Recycle	Gross Water Use	Use Rate (%)	Discharge	Consumption (consumption rate %)
Food	269.5	145.3	414.9	154	240.0	29.5 (10.9)
Beverages	73.1	18.3	91.4	125	56.2	16.9 (23.1)
Rubber Products	12.3	12.9	25.2	205	11.3	1.0 (7.8)
Plastic Products	13.3	38.7	52.0	392	12.0	1.3 (9.4)
Primary Textiles	86.7	68.2	154.9	179	84.6	2.1 (2.4)
Textile Products	15.0	7.9	23.0	153	12.9	2.1 (14.1)
Wood Products	45.1	10.2	55.3	122	33.0	12.1 (26.9)
Paper + Allied Products	2421.3	3105.9	5527.3	228	2207.0	214.3 (8.9)
Primary Metals	1423.0	1447.9	2870.9	202	1303.0	120.0 (8.4)
Fabricated Metals	19.4	8.1	27.5	142	18.4	1.1 (5.6)
Transportation Equipment	65.4	107.3	172.7	264	46.4	19.0 (29.0)
Non-metallic Mineral Products	102.3	91.8	194.1	190	83.1	19.2 (18.7)
Petroleum + Coal Products	370.5	541.4	911.9	246	348.0	22.5 (6.1)
Chemicals + Chemical Products	1121.3	1353.7	2475.0	221	1030.6	90.7 (8.1)
Total Manufacturing	6038.3	6957.7	12,996.0	215	5486.7	551.6
Total Thermal Power Generation	28,749	11,655	40,404	140	28,241	508 (1.8)

Use Rate = Gross Water Use as % of Water Intake (the higher the #, the greater the reuse)
Consumption = Intake - Discharge
Consumption Rate = Water Consumption as % of Water Intake
Source: Environment Canada (2002).

Thermal Power Generation Water Use

Intake for thermal power plants (mainly nuclear and coal power plants) totalled 28,750 MCM in 1996 (Table 1). Surface waters are the principal source of intake and discharge for this sector. Reuse rates increased significantly between 1991 and 1996, a possible result of tighter regulations and/or a stronger environmental ethic. Water use in the thermal power sector was concentrated in the regions with the highest recirculation rates and largest establishments – Ontario and the Prairie Provinces.

In summary, the following main observations characterize water use in the Canadian manufacturing and thermal power sectors.

- If one measures water use by total withdrawals, the thermal power generation sector, followed by the manufacturing sector, are the largest water users in Canada.
- The vast majority of this water supply is taken from self-supplied, surface freshwater sources. This is particularly the case for large users. Smaller establishments, which constitute by far the largest numbers of Canadian manufacturing establishments, draw much of their water supply from public utilities, largely because economies of scale do not justify dedicated, self-owned water supply facilities.
- The manufacturing sector, as a whole, has the highest water reuse rates relative to the other consumptive sectors (thermal, municipal, agricultural and mining).
- Consequently, if one measures water use by consumption (water that is not returned to its original source), the thermal power and manufacturing sectors are less likely to affect water availability than the municipal and agricultural sectors, although in many regions this may vary.

Trends

Future Demand

In spite of past efforts to define emerging industrial water demands (e.g., Tate, 1985; Tate and Harris, 1999, 2002), the "science" of water demand forecasting involves considerable uncertainty. Water is fundamentally a "derived demand," and, accordingly, is a function of many other variables, such as population levels, industrial output, water allocation regulations (including water pricing) and technological conditions. Because all these variables are themselves uncertain in terms of their future values, future water demand levels are even more uncertain. While a limited amount of research has been conducted in the past (see Renzetti, 2002, for an overview of these studies), this "uncertainty factor" is still dominant, making water demand projections quite speculative, increasingly so as the forecasting "time horizon" increases.

One approach to partially overcoming this uncertainty has been to formulate a range of possible future conditions, and make demand a function of these "futures." This has been the predominant methodology used in Canada for production of national-level water demand forecasts – last done in 1985 for the *Inquiry on Federal Water Policy* (Tate, 1985)[2]. But even the use of sensitivity analysis can be misleading. The above study estimated that manufacturing water intake would range from remaining relatively stable (under the conservation scenario) to increasing over threefold (under the high growth scenario) between the years 1981 and 2011. The available evidence, however, indicates that manufacturing water intake dropped between 1986 and 1996 (Environment Canada, 2002).

Regional projections of manufacturing water use have also been undertaken in Ontario (Tate and Harris, 1999, 2002) as part of a Canada-Ontario-U.S. initiative to develop baseline information required to improve sub-basin level water allocation decisions and better assess the implications of climate change[3]. Water use projections are always limited by a static picture of the economy, rendering this exercise a very uncertain science, and making the task of assessing implications for water availability equally challenging.

Determinants of Industrial Water Use

The limited research indicates that external charges, level of output, state of technology, environmental regulations, and prices of other inputs all play a role in determining water intake levels. For example, Dupont and Renzetti (2001) found that for the Canadian manufacturing sector as a whole, both intake and recirculation rates were sensitive to their respective unit costs with own-price elasticities (i.e., the measure of responsiveness of water demand to price changes) estimated at -0.8 and -0.7, respectively (Dupont and Renzetti, 2001; Renzetti, 1992).

This understanding of the determinants of industrial water use can assist us in explaining recent trends and anticipating future changes. For example, intake relative to output has fallen during 1981-1996. However, since most manufacturing water intake has not faced increasing prices (as it is mostly self-supplied), we must look to other explanations. Interestingly, Dupont and Renzetti (2001) found that technological change over the period 1981-1991 led to increased water intake and decreased recirculation. Given water's very small share in the costs of production, it is likely that this has been the result of firms' innovations to conserve on intermediate inputs and energy use rather than being directed at increasing water use per se. On the other hand, research conducted in other jurisdictions indicates that tightened regulations regarding allowable discharges in effluent streams appear to have reduced water intake and encouraged greater internal recirculation (Solley et al., 1999). Still, a number of important features, such as recirculation decisions, remain poorly understood.

Implications for Water Availability

Sector Pressures: As the nation's economy continues to shift towards knowledge-based manufacturing (e.g., computers and electronics, biotechnology, and pharmaceuticals) and service-oriented industries, there will likely be a demand for higher quality water, and these industries may invest significant amounts of money in their plants to produce ultra-pure water. Further, one might expect the demand for water to shift from a small number of large industrial self-supplied users to a growing number of smaller manufacturers more reliant on municipal water systems for their supply. This presents a real threat to Canadian industry given the deterioration in municipal water infrastructure documented over the last two decades (FCM, 1985; NRTEE, 1996). Beyond this speculation though, there is little documented analysis on the implications of this shift for water availability.

Regional Impacts: The major water consuming industries, and largest withdrawals, are still within the Great Lakes - St. Lawrence River basin. There are significant water quality issues here, due to contamination from municipal and industrial point sources and agricultural non-point sources. While point and non-point pollution also occur in the other basins in Canada, the magnitude is not as significant and extensive as in this basin. Interestingly, manufacturing plants are often both the primary causes and the injured parties of this water quality depletion. Depletion has led, for example, to increased costs of industrial water acquisition, in addition to the need to develop new public water supplies.

Smaller Watershed Impacts: Manufacturing withdrawals from smaller tributaries and rivers could have more severe ecological impacts. The hydrologic characteristics of smaller rivers are such that they exhibit large fluctuations of high and low flows between the spring snowmelt period and the summer. The summer low flow period is quite critical in that there may not be sufficient water available to meet the demands of all economic sectors. Furthermore, instream ecological requirements should first be met, before other withdrawals can be considered. Some provincial governments in Canada (e.g., Alberta, Ontario, Quebec) have responded to this need by re-evaluating their regulations governing the issuance of withdrawal permits.

The paper and allied products sector uses, and recycles, enormous quantities of water in Canada.

Seasonal Impacts: Manufacturing withdrawals are typically less of a threat during low flow periods. Aside from the agri-food processing industry, the manufacturing sector's water use is largely consistent throughout the year. Municipal water use, on the other hand, usually has a daily peak and a summer withdrawal rate that can be two to three times higher than the annual average flow.

Infrastructure Impacts: Based on experiences with municipal water treatment plants, it is possible that zebra mussels might clog the intakes of industrial plants. Further, there are likely to be problems with the outfalls or disposal of wastewater from industries because they could stir up the sediment from channel and lake beds. The resuspension of chemical-laden sediment may also affect water quality. Jay and Simenstad (1996) have noted that water withdrawals can affect downstream aquatic habitats and the fluvial regimes of sensitive ecosystems. Similar concerns have been noted by Boyce et al. (1993) concerning the impacts of water withdrawals and discharges for industrial and municipal cooling purposes.

Recycling and Water Quality: Recycling of water by manufacturers is slowly increasing. While there is a benefit in the form of reduced freshwater withdrawals, higher recirculation rates within the industrial process may generate higher concentrations of pollutants, eventually discharged into receiving waters. This could affect freshwater availability for other downstream uses.

Emerging Issues

Deregulation of the Electricity Market: The deregulation of the market for electricity generation and sales holds the potential for significant impacts on water use in Canada. There are several reasons for this. First, thermal and hydroelectric power plants use enormous quantities of water. Second, changes in the electricity market may change the temporal pattern of withdrawals by plants: that is, changes in electricity market conditions could make it necessary for plants, once used predominantly for base-load generation, to switch to supplying peak-load power (and the reverse). Third, depending on relative costs of production, there may be significant changes in the desired level of output from different plants, with some increasing output while others decrease or even cease production. Finally, pressures stemming from the implementation of the Kyoto Treaty and externalities associated with coal-powered power production may imply a long-term shift away from thermal production and toward hydroelectric power generations. All these factors and their implications for industrial water use in Canada are poorly understood but are of potentially local and national significance.

Climate Change Impacts: Little research exists on effects of climate change on industry and consequences for water use. Higher ambient temperatures imply greater cooling requirements at industrial plants, and, accordingly, increased water demands, particularly during the summer season. This increased demand may lead to increased competition among sectors for available water supplies. Should climate change mean decreased water flows or levels, these problems would be exacerbated. On the whole, predicting impacts on this sector is extremely difficult because climate change itself will alter the demand for some products, which changes the water needs of the individual manufacturer. What is known is that climate change will affect both the supply and demand for water, and therefore heighten the need for institutions and regulations to be sufficiently flexible and more efficient with respect to allocating water.

Bottled Water Industry: The Canadian bottled water industry has been growing rapidly in recent years. Output has grown at an annual rate of 9% since 1995. Still, by international standards, Canadians drink relatively little bottled water. The average Canadian drank approximately 20 litres in 1997 while the average per capita consumption level in Europe was between 100-140 litres. In addition, the bottled water industry is still quite small with a total annual output in 2000 of less than 1 million cubic metres (Dupont et al., 2002). Thus, this industry is not a major water user component of the manufacturing sector; however, it is one to monitor because of its rapid growth and potential for localized effects on aquifers.

"New Economy" Industries: Deteriorating water quality can substantially raise water treatment costs for some industries. Many require high quality water, even for cooling purposes. The so-called "new economy" industries (e.g., computer chip manufacturers) require water of high purity for their process operations. Thus, water quality degradation problems, often caused by industry, pose threats to other industries, and, more generally, to the population as well as the ecosystem. The impact on water supplies from a growing service sector in Canada, such as the local impact from large hotels in remote areas, remains poorly understood.

Knowledge and Program Needs

Knowledge/Research Gaps

Data: Data on water withdrawals, consumption, recycling, etc., are needed to quantify accurately how much freshwater is being used by industries, particularly at the watershed and sub-watershed levels. This need would indicate that national Industrial Water Use Surveys should continue.

Models: To reduce potential conflicts among various water users, especially during drought and low-flow periods, it is necessary to develop biophysical water allocation models that take ecosystem requirements into account. Ongoing initiatives in the Great Lakes basin to develop baseline information required to improve sub-basin water allocation decisions should be supported and encouraged elsewhere. Research on ecological water requirements is therefore important. It is also necessary to develop econometric models that better explain industrial water demands and recirculation decisions.

Monitoring: Impacts of wastewater disposal from major industries on downstream water availability should be monitored and assessed, and monitoring of effluent quality should be increased. Also, the quality of effluent from plants using significant amounts of recycled water should be continually monitored to help establish linkages between recycled water quantity and quality. The results of such a monitoring program will determine whether specific measures should be put in place to handle concentrated/polluted recycled water.

Technology Development: Development of water conservation technologies and water efficient manufacturing processes should be continuously encouraged.

Mapping Sensitive Ecosystems: There is a need for better understanding, knowledge and mapping of sensitive aquatic ecosystems in regions where large industrial water users are located. This will allow us to assess if and how aquatic organisms are likely to change as freshwater is withdrawn and wastewater is discharged into aquatic environments – identified as a priority by a study on the ecological impacts associated with Great Lakes water withdrawals (Limno-Tech, Inc., 2002).

Understanding Industrial Water Use: Relatively little is known regarding a number of features of industrial water use including factors influencing reuse decisions, the relationship between water and other inputs, the interaction between firms' decisions regarding water intake and water quality, and the value of alternative industrial applications of water.

Program Needs

Water Pricing: In Canada, most provinces do not have fees on water withdrawals for water consuming sectors. The perception that Canada is still a water-rich nation slows any institutional response to this, with obvious benefits for industry in the form of relatively assured and cheap water supplies. However, it also has a significant "downside," namely that almost no attention is paid to the nature of demands made upon the resource. There is some evidence that charging for water withdrawals helps encourage conservation while having relatively little impact on industry costs (Dupont and Renzetti, 1999; Tate et al., 1992).

Improved Incentives for Efficient Use: Although water reuse rates in Canadian manufacturing were up between 1991 and 1996, intake levels are still high compared to those of many other nations, largely because incentives for recirculation are weak or non-existent (Kollar and MacAuley, 1980). In many cases, elevated intake levels by industry have led to pressures on adjunct uses. Cheap water means little push for conservation measures, and other technological changes. Stronger efficiency-oriented incentives can have considerable impact on industrial water use.

Economic Instruments to Allocate Water Better: Water allocation issues involve the distribution of rights to use available water supplies. These issues can become critical in times of constrained water supplies. Throughout Canada, water allocation systems are quite primitive, involving administrative and economically free permitting systems, and enumeration of arbitrary lists of priority uses to be employed in periods of water shortage. There have recently been tentative first steps to develop water markets in Alberta, which would use economic mechanisms to influence water allocation (Horbulyk and Lo, 1998). These initiatives are modelled on water marketing arrangements now in operation in the southwestern United States. (Interested readers may consult the volume in which the Horbulyk and Lo chapter appears for further analysis of water markets.)

Promote Technological Innovation: Industries located in water-short regions face periodic, largely seasonal constraints on their water supplies. In the short term, this may translate into reduced production although there is widespread evidence that industries adapt to water shortages quickly through technological substitution, such as adoption of water recirculation and other measures aimed toward conservation (Hansen, 1994). For instance, in developing initial capital for plants in water-short regions, many industries design processes aimed at conserving water. A prime Canadian example is the Miller pulp and paper mill located in Meadow Lake, Saskatchewan, which has zero discharge of water, very high levels of recirculation and in-plant waste treatment, and withdrawal of only small amounts of water to make up for evaporative losses (Evans, 1994).

Technologies used by manufacturers to conserve water are too vast for description here. Some U.S. states have developed sector-specific water conservation guides (California Department of Water Resources, 1994; North Carolina Department of Environment and Natural Resources, 1998). In Canada, industry groups and governments at all levels have fostered water conservation typically through pollution prevention programs. Nevertheless, sharing of industry-specific, water-conserving, technological knowledge and innovation demands continued vigilance to garner further attention and action.

In summary, although the thermal power generation and manufacturing sectors withdraw large amounts of freshwater in Canada, they consume (water that is not returned to its original source) relatively less than some other sectors such as agriculture, although in many regions this may vary. Large industrial withdrawals from small rivers and streams are likely to be the greatest immediate threat to water availability.

Estimating future water demand in these sectors is fraught with uncertainty since so many factors (level of output, state of technology, environmental regulations, prices of other inputs) play a role in determining water intake levels. Electricity deregulation (which could result in some thermal and hydroelectric plants using more water to increase their peak-load production) and climate change (which may result in higher water use in response to greater cooling requirements in many manufacturing industries) are two emerging issues that warrant attention. The bottled water industry in Canada while currently not a major water user also requires monitoring because of its recent and continued rapid growth potential, which could have localized effects on aquifers.

Water withdrawal and consumption data to identify potential biophysical and socio-economic impacts and a better understanding of factors influencing industrial water use are critical data and research needs. Also, more attention is needed to send appropriate pricing signals when permitting water withdrawals, if technological innovation and improved water efficiency are to be encouraged. Currently, in many provinces, no fees or very small fees are charged for direct withdrawal of water (typically by large self-supplied thermal hydroelectric facilities and manufacturing plants). Finally, the role of economic instruments to allocate water more effectively requires investigation.

References

Boyce, F.M., P.F. Hamblin, D.L.D. Harvey, W.M. Schertzer and C.R. McCrimmon. 1993. Response of the thermal structure of Lake Ontario to deep cooling water withdrawals and to global warming. J. Great Lakes Res. 19(3): 603-616.

California Department of Water Resources (CDWR). 1994. Water efficiency guide for business managers and facility engineers, Sacramento, California.

Dupont, D.P. and S. Renzetti. 1999. An assessment of the impact of charging for provincial water use permits. Can. Public Policy 25(3): 361-378.

Dupont, D.P. and S. Renzetti. 2001. The role of water in manufacturing. Environ. Resour. Econ. 18(4): 411-432.

Dupont, D.P., S. Renzetti and J. Roik. 2002. Message in a bottle: water quality for sale. Presented at Drinking Water Safety: A Total Quality Approach Conference. Sept. 23-25, 2002, Ottawa, Canada.

Environment Canada. 2002. Industrial water use, 1996. Minister of Public Works and Government Services Canada, Ottawa, Ontario.

Evans, T. 1994. An overview of the water recovery process at Millar Western's Meadow Lake Mill, p. 347-357. *In* D. Shrubsole and D. Tate (ed.), Every drop counts. Canadian Water Resources Association, Cambridge, Ont.

FCM. 1985. Municipal infrastructure in Canada: physical condition and funding adequacy. Federation of Canadian Municipalities. Ottawa-Hull.

Hansen, T. 1994. Water management for water and cost saving through continuous improvement, p. 347-357. *In* D. Shrubsole and D. Tate (ed.), Every drop counts. Canadian Water Resources Association, Cambridge, Ont.

Horbulyk, T. and L. Lo. 1998. Welfare gains from potential water markets in Alberta, Canada, p. 241-257. *In* K.W. Easter, M. Rosegrant and A. Dinar (ed.), Markets for water: potential and performance. Kluwer Academic Press, Boston.

Jay, D.A. and C.A. Simenstad. 1996. Downstream effects of water withdrawals in a small, high-gradient basin: erosion and deposition on the Skokomish River Delta. Estuaries 19(3): 501-517.

Kollar, K.L. and P. Macauley. 1980. Water requirements for industrial development. J. Amer. Water Works Assoc. 72(1): 2-9.

Limno-Tech, Inc. 2002. Ecological impacts of water use and changes in levels and flows: a literature review. Prepared for the Great Lakes Commission, June 13, 2002, by Michel Slivitzky.

North Carolina Department of Environment and Natural Resources (NCDENR). 1998. Water efficiency manual for commercial, industrial and institutional facilities. Raleigh, North Carolina.

NRTEE. 1996. State of the debate on the environment and economy: water and wastewater services in Canada. National Round Table on the Environment and Economy, Ottawa.

Renzetti, S. 2003. Commercial and industrial water demands. *In* D.E. Agthe, R.B. Billings and N. Buras (ed.), Managing urban water supply: economic and hydrological analysis of urban water supply problems. Kluwer Academic Press, Norwell, Massachusetts, In press.

Renzetti, S. 1992. Estimating the structure of industrial water demands: the case of Canadian manufacturing. Land Economics 68(4): 396-404.

Renzetti, S. 2002. Introduction, p. 1-20. *In* S. Renzetti, (ed.), Economics of industrial water use. Edward Elgar, London.

Rodrigo, D., T. Blair and B. Thomas. 1996. Integrated resources planning and reliability analysis: a case study of the Metropolitan Water District of Southern California, p. 49-73. *In* D. Hall (ed.), Advances in the economics of environmental resources. JAI Press, Greenwich, Connecticut.

Solley, W., R. Pierce and H. Perlman. 1999. Estimated use of water in the United States in 1995. United States Geological Survey Circular 1200.

Statistics Canada. 2000. Human activity and the environment, 2000. Catalogue No. 11-509-XPE, Ottawa, Ontario.

Tate, D.M. 1985. Alternative futures of Canadian water use, 1981-2011. Inquiry on Federal Water Policy, Research Paper #17, Inland Waters Directorate, Environment Canada, Hull.

Tate, D.M. 1977. Manufacturing water use survey, 1972: a summary of results. Department of the Environment, Inland Waters Directorate, Social Sciences Series No. 17. Ottawa-Hull.

Tate, D.M. 1983. Water use in the Canadian manufacturing industry, 1976. Environment Canada, Inland Waters Directorate, Social Sciences Series No. 18, Ottawa-Hull.

Tate, D. and J. Harris. 2002. A water demand forecasting model and sample forecast for Ontario, 1996-2021. Report prepared for Environment Canada and Ontario Ministry of Natural Resources.

Tate, D. and J. Harris. 1999. Water demands in the Canadian section of the Great Lakes basin, 1972-2021. Unpublished report prepared for the International Joint Commission.

Tate, D.M., S. Renzetti and H.A. Shaw. 1992. Economic instruments for water management: the case for industrial water pricing. Environment Canada, Economics and Conservation Branch, Social Sciences Series No. 26, Ottawa.

Tate, D.M. and D.N. Scharf. 1992. Water use in Canadian industry, 1986. Environment Canada, Water and Habitat Conservation Branch, Social Science Series No. 24, Ottawa-Hull.

Tate, D.M. and D.N. Scharf. 1995. Water use in Canadian industry, 1991. Environment Canada, Water and Habitat Conservation Branch, Social Science Series No. 31, Ottawa-Hull.

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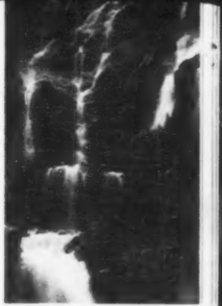
[1] Canada is one of the few countries with a regular survey of industrial water use. Information on manufacturing and thermal water use for this report comes from Environment Canada's 1996 Survey of Industrial Water Use (Environment Canada, 2002), and is compared with previous estimates and research in Tate and Scharf (1995, 1992), Tate (1983, 1977), and Dupont and Renzetti (2001).

[2] The reader is referred to Tate (1985) for a complete outline of this methodology.

[3] See http://www.on.ec.gc.ca/water/water-use/, and http://www.glc.org/waterquantity/wrmdss/ for more information on these initiatives.

Chapter 7

LAND-USE PRACTICES AND CHANGES – AGRICULTURE



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Current Status

Land and Water Use

Agriculture accounts for 3.0% of Canada's gross domestic product, making it one of the largest sectors in the country. Approximately 7% of Canada's land base is used for agriculture, amounting to 67.5 million ha. Prairie Provinces account for 82% of this total, while Ontario and Quebec contribute only 13%, although the productivity in these two provinces is generally greater on a per hectare basis. Of the agricultural land base, 46 million ha are improved farmland such as cropland and summerfallow, with 20 million ha as unimproved pasture land (Statistics Canada, 2002).

Although agriculture is not Canada's largest user of water, it is the largest net consumer. Nationally, 44.61 billion m^3 of surface water are withdrawn by major users from Canada's rivers (1996). However agriculture (1991) withdrew only about 9% compared with thermal power (64%) and manufacturing (14%). Even though, overall, only about 10% (4.5 billion m^3) of water withdrawn is actually consumed, agriculture consumes 71% of the water it diverts, making it by far the greatest consumer. Furthermore, there are marked differences among Canadian regions related to agricultural water use. About 85% of agricultural withdrawals (surface and ground water) are used for irrigation (primarily in the West) and 15% is used for watering livestock (Environment Canada, 2002a,b). Groundwater use, though relatively small in comparison to surface water volumes, provides 26% (6.2 million people) of domestic water supply overall, with 82% of rural Canadians (about 4 million people) relying on groundwater for supply (Science Council of Canada, 1988).

Sustainable agricultural development and an increase in improved farmland require continued access to reliable, good quality water resources. The importance of water to agriculture cannot be overstated. Agriculture's use of water for irrigation of crops, livestock watering, processing, and sustaining farm families in urban and rural areas alike is of utmost importance.

Impacts of Farming on the Hydrologic Cycle

As agricultural land use in Canada has increased, the natural hydrology of the landscape has changed, affecting the relative availability and in some cases the quality of water. It is widely perceived, but not well understood, that the quality of surface and ground water is likely deteriorating in agricultural areas due to increased loading from nutrients, pesticides and pathogens.

The production of crops in both irrigated and rain-fed systems affects water flow in the landscape. The diversion and redistribution of water through irrigation and drainage have significant impacts on the natural hydrologic cycle. Crop type and management can change infiltration and flow of water through the soil profile, and hence modify patterns of surface and subsurface flow. This combination has sometimes resulted in increased peak runoff events and silt loading to rivers, decreased base flows in small streams and waterways, and reduced surface infiltration on which groundwater recharge in some areas may be dependent to sustain wetlands and water supply.

Effects of crop type on runoff and sediment loss are well known. Runoff is likely to be less with those crops that provide permanent soil cover such as pasture, hay and perennial horticultural crops like tree fruits that have a grass cover.

Conservation Tillage: For annually seeded crops, conservation tillage practices, developed and widely accepted over the past 15 to 20 years can greatly reduce surface losses of water, sediment and nutrients to waterways. Under such practices, a 30% or greater cover of residue from the previous crop is left on the soil surface. For example, a 60% reduction in surface runoff was reported for no-till corn in Quebec when compared with conventional tillage (McRae et al., 2000). In Saskatchewan, at the watershed scale, snowmelt runoff from long-term, zero-tillage was less than half that from conventionally tilled fields, and runoff from summer storms was also reduced (Elliott et al., 1998). Adoption of conservation tillage practices has resulted in fewer days when soils are left bare and exposed to erosion. McRae et al. (2000) reported that between 1981 and 1996, the number of bare soil days per hectare per year was reduced by 2% in Quebec, and 44% in Newfoundland, with the average for Canada being around 20%.

Drainage and Irrigation: Due to Canada's climatic conditions, systems for both good drainage and irrigation are often essential for successful agricultural production. In eastern Canada and the coastal areas of B.C. where there is a surplus of precipitation at certain times of the year, drainage is required to remove excess soil water. Natural internal drainage and surface drainage are insufficient to ensure that the water table is lowered rapidly enough for early seedbed preparation and planting. Therefore, artificial drainage in the form of horizontal subsurface drains ("tile" drainage) is often required to provide better conditions for farm machinery operation.

Conversely, irrigation may be required on the Prairies and other regions of Canada where the range in annual precipitation (as low as 300 mm in southwest Saskatchewan to 550 mm in Beausejour, Manitoba) is often insufficient to meet the evaporative demands placed on crops. In regions where irrigation is widely practiced (predominantly Alberta and British Columbia), up to 35 to 40% of annual precipitation within affected watersheds is diverted for irrigation purposes. This constitutes a major change from the natural hydrologic processes in these basins.

Drop tube irrigation system - conserving water and energy.

Consumptive Use – Irrigation

Much of the water required for irrigation throughout the growing season must be captured during spring snowmelt and stored behind dams or in reservoirs for later use. This storage promotes significant evaporative losses throughout the year. In addition, the diverted water that is ultimately used in crop production results in gaseous losses through evapotranspiration, which will generally exceed those losses found under natural vegetation cover. The remainder of the diverted irrigation water is unavailable to crops, either being stored in the soil below the rooting zone, lost to groundwater, or is returned to river systems through surface flow.

About 75% of all agricultural water withdrawals in Canada take place on the Prairies, mainly for irrigation. Alberta has approximately 630,000 ha of irrigated land, or about 60% of the total irrigated cropland in Canada. In the South Saskatchewan River basin (SSRB) of Alberta, irrigation consumes about 2.2 billion m^3 of water each year from the river system, equivalent to 28% of the total annual river flow. Under the Apportionment Agreement with the Prairie Provinces, 50% of the annual natural flow of water in the SSRB must flow to Saskatchewan. Apportionment and irrigation therefore account for 78% of the current Alberta water commitments in the SSRB, leaving about 22% of the flow for all other uses, including municipal, industry and the environment. As a result of increased water demands from all sectors, some Alberta watersheds are near or at full allocation and under water diversion moratoriums.

The challenge for agriculture has been to adopt management practices that will optimize the amount of water diverted per unit of crop yield, through improved efficiencies in storage, distribution, and on-farm utilization. As an example, the St. Mary River Irrigation District in Alberta has reduced the total amount of diverted water "lost" in return flows to the river system to less than 7%. This is indicative of more efficient usage and thus a smaller requirement for diversion per unit of crop produced. These efficiencies have resulted from the development of internal storage reservoirs, lining of irrigation canals, replacement of surface canals by pipelines, and conversion of flood irrigation systems to high efficiency pivot sprinkler systems (Irrigation Water Management Study Committee, 2002).

The majority of irrigation in Canada is through sprinkler systems. This type of irrigation has significantly less impact on surface hydrology than traditional flood irrigation. Flood irrigation often results in surface water losses of up to 50% (Irrigation Water Management Study Committee, 2002). In Alberta, the change from flood irrigation to pivot sprinkler irrigation has essentially eliminated these losses. In British Columbia, the use of micro-irrigation systems (trickle or drip irrigation) has further increased the optimization of water use for crop production, and has the potential to eliminate surface loss and restrict subsurface losses.

The present focus is to improve irrigation effectiveness through higher efficiency irrigation systems, improved water management, scheduling irrigation to meet crop water demands, suppression in evaporation losses and production of higher value crops. In British Columbia's Okanagan Valley, irrigation methods started with flood irrigation in the 1940s. These systems were converted to more efficient sprinkler irrigation methods in the late 1950s and 1960s. Today, 30% of the fruit tree growing area has converted from sprinkler irrigation to micro-irrigation systems that offer an increase in efficiency of 70% to 90% over sprinkler methods (Ted van der Gulik, personal communication). Mulches are being used to reduce evaporative losses in horticultural crops. For newly planted trees, the reduction in evaporation losses has been shown to be as much as 50%, but reduces to 10% as the trees get larger.

In Alberta, conversion from flood irrigation to more efficient centre pivot systems has increased irrigation system efficiencies by 40%. Seepage losses in 1991 from canal systems in the 13 irrigation districts were estimated to be 471.76 million m^3. A more detailed analysis in 1999 following extensive rehabilitation efforts showed that seepage losses were 89.75 million m^3. It is estimated that projected canal rehabilitation will further reduce seepage losses to about 54 million m^3, which represents 1.5% of the gross volume of water diverted on an annual basis (Irrigation Water Management Study Committee, 2002).

The current demand for irrigation in eastern Canada is relatively small. This is because the region usually experiences an annual surplus of precipitation over evapotranspiration. The total land area irrigated in the region is approximately 100,000 ha. This is mainly for high value horticultural crops in the fruit and vegetable industries. Irrigation is required during the months of June, July and August, to supplement rainfall and help meet crop evapotranspiration requirements. The main methods of irrigation in eastern Canada are sprinkler and drip systems.

The shift to efficient irrigation systems does not necessarily translate into water savings unless these systems are managed correctly. Advances in irrigation scheduling technology (using soil moisture or climate/weather data), allow farmers to schedule water applications on a daily basis. In British Columbia, irrigation scheduling with fully automated systems controlled by units that monitor evaporative demand (Parchomchuk et al., 1996), has been shown to reduce water use by 20 to 30% (Neilsen and Neilsen, 2002).

Need for Reliable Potable Water: In some areas, buyers are starting to require farm audits confirming that potable quality water is being used to irrigate and wash crops that are sent to the fresh market. Many surface water supplies will not meet such requirements without some form of treatment, which may prove difficult to obtain. There is, accordingly, a trend towards the use of groundwater, even though the resource is poorly understood in many parts of the country.

Consumptive Use – Livestock

Livestock production is an important component of Canada's agri-food industry. At present, approximately 15.5 million head of cattle and calves, 14 million head of hogs and 140 million poultry are produced throughout Canada (Statistics Canada, 2002). Production of quality livestock requires a stable supply of high-quality water, as indicated in Table 1. Groundwater provides nearly all of the water used to produce livestock in Canada (Science Council of Canada, 1988).

In some areas of the country, such as Quebec, expansion of the intensive livestock industry has been restricted as a result of concerns about water quality. Current livestock management promotes reduced water use through improved techniques. For example, in dairy operations water can be saved through initiatives that include: scraping or sweeping milkhouse floors before washing, reusing equipment rinse water to wash floors, using high pressure nozzles for washing, installing water-saving sinks, and using the first rinse water from milk lines to water calves.

Drainage Effects

The beneficial effects of land drainage for crop production are well understood. Surface drainage systems include shallow ditches designed to drain surface depressions in fields, and deeper ditches designed to intercept overland flow and seepage, and to prevent water from re-entering agricultural land. Such systems eventually drain into natural waterways. Surface drainage systems may increase runoff, which may be of poor quality and contain high quantities of nutrients, agri-chemicals and sediment. Soil conservation techniques, such as grassed

Table 1. Daily water needs of farm animals[1]

Animal type	Water (L/day)
Beef feeder	35
Beef cow	55
Dairy cow	160
Lactating sow	20
Feed pig	10
Ewe	7
Chicken layer	0.25–0.30
Chicken broiler	0.15–0.20

[1] From Agriculture and Agri-Food Canada (2000), *Health of Our Water - Toward Sustainable Agriculture in Canada.*

waterways and buffer strips, have been shown to significantly reduce over-land movement of water and to improve the quality of water in surface drains (Table 2). Considerable work is required to further clarify the value and to achieve universal adoption of a range of such beneficial management practices throughout Canada.

Subsurface drainage systems can influence the downstream quality of surface drainage waters by transporting large volumes of water (which may contain pathogens, nutrients and agri-chemicals) into natural watercourses. One method of controlling water and nutrient losses from subsurface drainage is through a water table management system. This system has been used successfully in Quebec (Madramootoo et al., 2001) and in Ontario (Drury and Tan, 2000). Water drainage is reduced at specified times in the growing season and stored water may then be used for subsurface irrigation during periods of water shortage. Reduced water losses through tile drains resulting in decreased nitrate losses of up to 39% have been demonstrated using this technique. Losses of nutrients and water to tile drains may also be reduced by planting winter cover crops which act as a sink for nutrients and water at the end of the main crop growing season (Milburn et al., 1997).

Table 2. Seasonal runoff from potato rotations under different management in New Brunswick[1,2]

Crop and year	Accumulated rainfall (mm)	Diversions and grass waterways		Up and down slope cultivation runoff (mm)	
		Runoff (mm)	Soil loss (kg/ha)	Runoff (mm)	Soil loss (kg/ha)
Grain/ryegrass 1990	707	32	106	25	285
Potatoes 1991	582	42	1678	203	15,604
Barley 1993	687	8	63	34	489

[1] From: Table 8-3, Agriculture and Agri-Food Canada (2000), *Health of Our Water - Toward Sustainable Agriculture in Canada.*

[2] Source: McRae et al. (2000).

Future Trends and Emerging Issues

Land and Water Use

Market conditions require that Canada's farmers provide cost-efficient, high-quality food for a growing world population. This will mean more competition for instream flow, and for the use and regulation of water bodies, resulting in more pressure to further develop water resources, diversions and conveyance, with attendant social and environmental considerations.

The Relative Cost of Water: Increased competition with instream users (such as fisheries and recreation) and consumptive uses (such as domestic and other industries), will require agriculture to respect the true economic value of water and ensure optimum use is attained. Increasing demand and a willingness to pay on the part of high-value enterprises, such as rural subdivision, golf courses, and water recreation, are increasing pressure on agriculture to seek alternate supplies such as municipal effluent, or to make their supplies available by simply selling their lands or water rights.

The Hydrologic Cycle

Expansion of the agricultural land base, and increasing agricultural demands for water and water management, have the potential for further impacts on the hydrologic cycle. But this incremental effect may be much less than previously, due to the adoption of on-farm beneficial management practices such as conservation-tillage. Still, there are tradeoffs even with these actions, and practices that reduce one hazard (e.g., surface runoff and soil erosion) may well enhance risks associated with another. For example, although minimum-tillage may reduce losses of water and some pollutants to surface drainage, this practice may increase infiltration into the soil and leaching to groundwater. This can enhance the movement of mobile nutrients and some pesticides to subsurface drains and to deeper groundwater along preferential pathways (e.g., cracks and worm holes) in the soil profile (Drury et al., 1996; Gaynor et al., 2002; Drury and Tan, 2000).

Increased percolation may also reduce anticipated overland flow to local sloughs and storage ponds. As well, the higher organic matter content in reduced-tillage fields such as no-till tends to filter the coarse soil particles from runoff, thereby enhancing the ratio of fine to coarse soil particles in runoff (Bernard et al., 1992). The decomposing organic matter in reduced-tillage fields can also bring about increased concentrations of soluble nutrients, particularly phosphorus, in surface runoff (Pesant et al., 1987). Such increased nutrient loadings might even be sufficient to offset the benefits of an otherwise reduced volume of runoff, by enhancing the potential for eutrophication.

Past agriculture programs (e.g., Agriculture and Agri-Food Canada's *Permanent Cover Program*) have encouraged the removal of marginally productive agricultural lands from annual cropping, returning them to long-term permanent cover under alfalfa hayland and pasture. The newly announced national *GreenCover* program, part of Agriculture and Agri-Food Canada's new Agriculture Policy Framework (Agriculture and Agri-Food Canada, 2002) is an expansion of that thrust. Such steps will tend to further reduce surface runoff and enhance groundwater recharge, while further filtering potential loadings to streams of sediment, nutrients, pesticides, and in some cases pathogens.

Consumptive Use – Irrigation

An increasing demand for more dams, reservoirs, and diversions will come with increased demand for irrigation. As already indicated, many watersheds now have their water resources fully allocated and greater irrigation efficiencies will be required if irrigation acreage is to expand, while maintaining acceptable streamflows for other uses. In limited areas, improved irrigation efficiencies may actually dictate an increase in irrigation water used per unit of land, where crops are now receiving insufficient water for optimum growth. For example, in Alberta and British Columbia, evaluation of irrigation system practices found that for some crops, producers were under-irrigating and could improve production by increasing the amount of water applied (Ted van der Gulik, pers. comm.; Irrigation Water Management Study Committee, 2002). Continued improvements in irrigation and conveyance efficiencies will free up some water for other uses.

Wireless and computer technologies might allow farmers to obtain required irrigation scheduling data directly from local weather stations. This technology can also be used to evaluate and monitor crop diseases that are climate based, reducing the amount of chemical pest control applications and the exposure window of water supplies to chemicals. Additional weather stations are required in agricultural areas. As well, GPS-type monitoring might be used for soil and crop moisture, similar to that being employed for fertilizer and pesticide applications. The challenge remains to have the technology adopted by the majority of crop producers in order that the efficiencies gained become fully realized, in the form of reduced water use and improved water quality on a watershed scale.

The cost of farming is also causing the agriculture industry to increase its use of water resources. Expensive farmland that was not irrigated before is being converted to produce higher value crops that often require irrigation to ensure that production levels can be maintained annually. As agriculture progresses toward crop diversification and the planting of higher value crops, it is likely that water demand will generally increase.

Increased water use is required for irrigation systems that now serve crop cooling and frost protection functions to ensure productivity and quality. Nutrient delivery to crops through irrigation systems, in an effort to improve nutrient management, may result in increased water use. In eastern Canada, not only will there be an expected increase in water demand as farmers move towards the planting of higher value horticultural crops, but also because of the fact that severe droughts have been experienced in the region over the past few years.

Wider Need for Potable Water: Water for irrigation and washing of plant products that are eaten raw requires potable water quality, as does the adoption of improved quality assurance programs on dairy farms. Treatment costs which will be required as most surface water sources are not considered potable without some level of treatment, may be significant. The trend towards the increasing use of, as yet often poorly defined groundwater resources, will continue. Competition between agricultural and domestic users for potable water sources and the associated infrastructure required can be expected to increase.

Consumptive Use – Livestock

It is expected that the intensive livestock industry, driven by provincial policy targets to increase livestock production, will continue to grow in some regions of Canada (Agriculture and Agri-Food Canada, 1998). This may be limited because of the increased competition for water, or constraints to land and water quality presented by manure management.

Drainage

Awareness is increasing as to the potential impact that drainage systems have on soil moisture relationships, and on both surface and ground water volumes and quality. Drainage system design will increasingly take these factors into account.

Agriculture and Climate Change

Effect of Climate Variability on Agriculture and Water Demand: Issues of climate variability and climate change are expected to have significant effects on agricultural practices, which in turn will affect water demand and availability. Climate variability is encouraging an increase in the adoption of irrigation to ensure higher yields and to compensate for drought stresses. For example, contracts for potato production in Manitoba require the availability of irrigation water in times of drought. Irrigation use for frost protection is increasing as is misting to cool crops.

It is generally recognized that climate change has the potential to have the greatest impact on the Prairies and in central B.C. Changes reflected in the hydrographs of snowmelt streams in response to recent climate variability (which may affect the timing of water availability), have already been documented (Leith and

Whitfield, 1998; Whitfield, 2001). In addition, glacial melt-water flows, which contribute significant volumes of water to rivers such as the Bow (Alberta) and Columbia (B.C.) during the summer months, will cease to exist as key glaciers disappear within the next 50 to 60 years. This will have significant impacts (10% of flow) on water availability for irrigation and instream flows for the protection of aquatic life. Additional storage may therefore be required on these rivers in order to meet all water demands and pressure to use more groundwater can be expected.

Climate change is expected to result in increased average temperatures across Canada. For example, based on climate change modelling, projections indicate a 37% increased demand for irrigation water in the Okanagan Valley, B.C., which may exceed availability in irrigation districts dependent on tributary streamflow (Neilsen et al., 2001). In addition, the area where crops require irrigation may increase northward in the Prairies, and east to Ontario, Quebec and the Atlantic Provinces.

Effect of Agriculture on Climate Change: Agriculture may contribute to climate change largely because of the release of the key greenhouse gases methane and nitrous oxide, and ways are being sought to reduce their production (e.g., carbon sequestration, improved fertilizer application).

Knowledge and Data Needs

Knowledge and data needs relating to threats to freshwater availability, both to, as well as from, agriculture and its land use practices, have been grouped into four main categories as follows.

Understanding Water Balances

Agriculture not only consumes water, but irrigation and drainage practices also contribute to the recharge of groundwater aquifers and the generation of runoff to surface waters. A better understanding of agricultural needs for water and the balance between its water demands and returns to the ecosystem is needed. There is good knowledge on water use for many crops grown in Canada. However, in irrigated systems, much of this knowledge is based on outdated assumptions related to irrigation technologies of the past. There is a general need to better understand:

- the potential for using less water: including the development of more drought-tolerant crops, and the use of lower moisture-use crops and management practices to optimize crop production, particularly during times of water shortage;
- water use requirements of specialty crops: for many of the high value and niche market species being introduced to Canadian agriculture and horticulture;
- regional water uses: including knowledge of the volumes of water withdrawn, used for irrigation and returned (e.g., this information is quite good in Alberta, but is generally lacking in other areas);
- agriculture and wetlands relationships: including the effect of agricultural water use and drainage on wetlands and riparian areas, and the base streamflows necessary to protect aquatic life;
- land management effects: on the soil water balance and partitioning of precipitation, and how this influences water availability for all users, at scales ranging from the field to a region; and
- potential climate impact: including variable weather and climate change, on agricultural water needs and the availability of water, as well as the effect of land management on the water-related consequences of climate variability.

There is also a need to:

- establish and maintain monitoring networks: to identify long-term trends in water harvesting, use, and quality under different land management practices;
- document groundwater supplies: to understand their extent, availability and quality. While this natural resource is often poorly understood, it is widely believed that the quality of surface and ground water may be deteriorating in agricultural areas (pesticides, nutrients and pathogens); and
- enhance local weather forecasting (Mesonet scale): with increased station density nationally, to optimize water use and support climate monitoring and prediction in agricultural areas.

Clarifying Institutional Frameworks

We need an improved understanding of the proper role of institutions in the allocation and protection of water resources used by agriculture. This includes a requirement for clear policies on water allocation, particularly during times of water shortage and between competing uses.

Employing Integrated Strategies

Effective progress requires the adoption of integrated planning and adaptive techniques to reduce agricultural threats to water availability. These should include:

- a watershed approach: incorporating appropriate agricultural practices into integrated watershed management plans to account for numerous water use activities;
- water reuse: promoting water reuse where practical, including urban wastewater use by agriculture, such as from the canning and processing industries;
- enhanced decision making: developing decision support and information systems, to improve water use efficiency and increase understanding of groundwater availability and vulnerability to agricultural practices; and

- adaptation strategy: incorporating processes to reduce the impact of climate variability on the need for water.

Sustained Agricultural Productivity

More intensive use of land for agricultural production, including increased areas under irrigation will continue in Canada. To deal effectively with existing and emerging water availability issues, specific actions in the following three generalized areas will clearly be required:

- targeted monitoring: investment in targeted monitoring is required to determine trends, assess limitations, and conduct ecological impact assessments of the effects of agricultural practices on water availability;
- research: continued research to ensure that the best knowledge and technologies are available for land and water management with emphasis on reduced crop water needs and improved water use efficiency; understanding the effect of land management practices on water availability, runoff/leaching characteristics and water quality and wetlands relationships; and exploring opportunities for water reuse and improved drought-adaptive strategies; and
- develop standards and codes of practice: the development and adoption of scientifically credible practices and standards and codes for agricultural enterprises is required to ensure protection of surface and ground water availability.

References

Agriculture and Agri-Food Canada (AAFC). 1998. Challenges and implications arising from the achievement of CAMC's 2005 agri-food export target. Agriculture and Agri-Food Canada, Policy Branch, Economic and Policy Analysis Directorate, Ottawa, Ont., Canada. 54 p.

Agriculture and Agri-Food Canada (AAFC). 2000. The health of our water: toward sustainable agriculture in Canada. Agriculture and Agri-Food Canada, Research Branch.

Agriculture and Agri-Food Canada (AAFC). 2002. Putting Canada first - an architecture for agricultural policy in the 21st century. Available from www.agr.gc.ca/cb/apf/ what_is-2_e.html; internet. Cited 10 November 2002.

Bernard, C., M.R. Laverdière and A.R. Pesant. 1992. Variabilité de la relation entre les pertes de césium et de sol par érosion hydrique. Geoderma 52: 265-277.

Drury, C. and C.S. Tan. 2000. Water table management system in Ontario, p. 98. *In* D.R. Coote and L.J. Gregorich (ed.), The health of our water. Research Planning and Coordination Directorate, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ont.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya and T.W. Welacky. 1996. Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss. J. Environ. Qual. 25: 317-324.

Elliott, J.A., A.J. Ce[illegible]a and D.W. Anderson. 1998. Effect of tillage system on snowmelt runoff quality and quantity. *In* Proc. Ann. Meeting of the Amer. Soc. Agron., Crop Sci. Soc. Amer. and Soil Sci. Soc. Amer., October 18-22, Baltimore, Md.

Environment Canada. 2002a. Freshwater website: the management of water: water use: withdrawal uses, 1991/96. Available from www.ec.gc.ca/water/en/manage/use/e_wuse.htm, Internet. Cited 6 March 2003.

Environment Canada. 2002b. Freshwater website: the management of water: water use - agriculture. Available from www.ec.gc.ca/water/en/manage/use/e_agr.htm; Internet. Cited 6 March 2003.

Gaynor, J.D., C.S. Tan, C.F. Drury, T.W. Welacky, H.Y.F. Ng and W.D. Reynolds. 2002. Runoff and drainage losses of atrazine, metribuzin and metolachlor in three water management systems. J. Environ. Qual. 31: 300-308.

Irrigation Water Management Study Committee. 2002. South Saskatchewan River basin: irrigation in the 21st century. Vol. 1: summary report. Alberta Irrigation Projects Association, Lethbridge, Alberta.

Leith, R.M. and P.H. Whitfield. 1998. Evidence of climate change effects on hydrology of streams in south-central B.C. Can. Water Resour. J. 23: 219-230.

Madramootoo, C.A., T.G. Helwig and G.T. Dodds. 2001. Managing water tables to improve drainage water quality in Quebec, Canada. Transactions of the ASAE 44(6): 1511-1519.

McRae, T., C.A.S. Smith and L.J. Gregorich (ed.). 2000. Environmental sustainability of Canadian agriculture: report of the agri-environmental indicator project. Agriculture and Agri-Food Canada, Ottawa, Ont.

Milburn, P., J.A. MacLeod and S. Sanderson. 1997. Control of fall nitrate leaching from early harvested potatoes on Prince Edward Island. Can. Agric. Eng. 39: 263-271.

Neilsen, D. and G.H. Neilsen. 2002. Efficient use of nitrogen and water in high density apple orchards. Hort Technol. 12: 19-25.

Neilsen, D., S. Smith, W. Koch, G. Frank, J. Hall and P. Parchomchuk. 2001. Impact of climate change on crop water demand and crop suitability in the Okanagan Valley, British Columbia. Tech. Bull. 01-15. Pacific Agri-Food Research Centre, Summerland, B.C. 32 p.

Parchomchuk, P., R.C. Berard and T.W. van der Gulik. 1996. Automated irrigation scheduling using an electronic atmometer, p. 1099-1104. *In* C.R. Cramp, E.J. Sadler and R.E. Yoder (ed.), Evapotranspiration and irrigation scheduling. ASAE Proc. Intl. Conf., San Antonio, Tex.

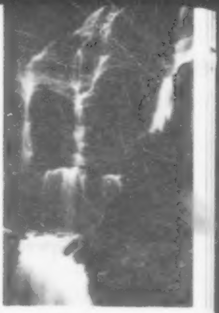
Pesant, A.R., J.L. Dionne and J. Genest. 1987. Soil and nutrient losses in surface runoff from conventional and no-till corn systems. Can. J. Soil Sci. 67: 835-843.

Science Council of Canada. 1988. Water 2020: sustainable use for water in the 21st century.

Statistics Canada. 2002. Available from www.statcan.ca; Internet. Cited 2002.

van der Gulik, T. Personal communication.

Whitfield, P.H. 2001. Linked hydrologic and climate variations in British Columbia and Yukon. Environ. Monit. Assess. 67: 217-238.



Chapter 8

LAND-USE PRACTICES AND CHANGES – FORESTRY

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Current Status

Canada has about 10% of the world's forests (418 million ha) and about 20% of the planet's freshwater resources (but only about 7% of the planet's renewable freshwater resources; CFS, 2002; EC, 2003). Forests recycle water to the atmosphere, thereby decreasing water transport into ground and surface water. They also filter air and water, moderate climate, provide habitat for wildlife, stabilize soil, and form a dominant feature of Canada's economy, culture, traditions, and history. Because of these attributes, forested watersheds provide a range of important services to humans and society, including provision of clean stream water and support of healthy aquatic ecosystems. For example, a number of major urban centres derive some or all of their water supplies from forested watersheds. Natural disturbances (e.g., insect defoliation and wildfires) and anthropogenic influences (e.g., fire suppression and timber harvesting) can temporarily alter the equilibrium of the hydrologic cycle by altering groundwater recharge-discharge dynamics, the position of the water table, and streamflow regimes.

Except for harvesting activities, fire and insect infestations are the dominant stand-renewing agents in most Canadian forests. For example, infestations of spruce budworm sweep through eastern boreal and maritime forests at approximately 35-year intervals, causing major stand renewal events and shifts in stand age structure. Wildfire has a greater immediate impact than insect infestations on forest hydrologic cycles because of its sudden nature and its profound alteration of organic matter. Fires occur regularly in the boreal forest, the mean fire cycle being 126 years (CCFM, 2002), with a range of 63 to 185 years (Bergeron, 1991; Larsen, 1997; Larsen and MacDonald, 1998). Fire is more frequent in the coniferous forests of west-central Canada (northwestern Ontario, Manitoba, Saskatchewan, and Alberta), and less frequent in the wetter forests of central and eastern Canada (Ontario, Quebec, and the Atlantic Provinces) and the Pacific maritime ecozone (mean fire cycle of 770 years) (Stocks et al., 2002). Fire frequency is a function of fuel quantity, quality, and dryness as well as fire weather; the conditions affecting the formation and spread of wildfires, including wind speed, thunderstorms, and stability of air systems. In Canada, the driest and windiest region is west-central Canada, and this is also where fire is most frequent.

Forest hydrology research in Canada was strongly supported by government in the late 1960s and early 1970s, a period known as the International Hydrological Decade. Gauges were set up and monitored in many watersheds, and a variety of studies examined the most immediate impacts of clear-cut harvesting practices on streamflow and erosion. The results of these studies were used in developing current forest management practices, which protect Canada's soils and freshwater resources. Although most harvesting operations still involve a one-pass removal system ("clear-cutting"), gradual removal approaches, including selection cutting, shelterwood cutting, and seed tree cutting, are increasingly used in Canada. The overall size of clear-cuts generally has been reduced, and the number of unharvested strips ("leave" strips) within cutblocks has increased, which has increased cutblock heterogeneity.

Across Canada, there are few comparable data on the effects of forest fires on watershed hydrology (Schindler et al., 1980; Bayley et al., 1992), but the immediate impact of a burn on streamflow volume and timing appears to be similar to that of a clear-cut. This similarity might be expected because in both types of disturbances the transpiring vegetation is removed, which results in decreases in evapotranspiration (ET) (Amiro et al., 1999; Amiro, 2001). However, differences in harvesting and fire in particular, with respect to interception of precipitation by logging debris and post-disturbance recovery, make any similarities less certain.

This chapter outlines the major impacts of timber harvesting and fire on forest hydrology and the subsequent impacts on freshwater availability, with emphasis on the boreal forest, the largest forest region in Canada.

Trends

Timber Harvesting

Canada's land area is about 922 million ha, of which about 418 million ha are forested. Commercial forests (capable of producing commercial tree species as well as other non-timber benefits) represent about 235 million ha, of which about 119 million ha are managed and about 1 million ha are harvested annually. The largest areas are harvested in Quebec and British Columbia (349,113 ha and 204,472 ha in 2000, respectively; CCFM, 2002). Seventy-one percent of Canada's forests are controlled by provincial governments, 23% by the federal government, and 6% by private landowners. Softwood species are harvested most often (86% of the total commercial timber harvest in 1995), primarily for the production of pulp and paper and for export. However, the harvest of hardwood species, used primarily to produce oriented strand board, laminated veneer lumber, furniture, flooring, plywood, and moldings, was 6% greater in the period 1990 to 1995 than the average pre-1990s hardwood harvest. This trend reflects the evolution of the forest products industry over the past 25 years and is predicted to continue. Harvesting rates were below Annual Allowable Cut rates for the period for which records are available, from 1970 to 1999 (CCFM, 2002).

Canada has evolved from a colonial supplier of wood products to European countries in its early years to a major international player in forestry. Because Canada is still growing, land-use changes, including those arising from urbanization, oil and gas exploration, mining, and agriculture, infringe on forests across Canada, most prominently in the southern boreal forest, the Carolinian forest, and the aspen parkland forest (CCFM, 2002). However, although some forest is being lost near urban centres, there are also gains in forested areas on marginal agricultural lands and in urban areas, the so-called urban forests (CCFM, 2002).

Forest fire south of Lake 240 in the Experimental Lakes Area in northwestern Ontario.

Current timber harvesting regulations in the provinces and territories generally strive to maintain a productive forest land base. Following the removal of timber, most harvested areas are allowed to regenerate naturally, the remainder being actively seeded or planted (CFS, 2002). The extent of seeding and planting varies considerably in accordance with the diversity of forest conditions and provincial and territorial policies. Since 1975, silvicultural practices adopted by the provinces and territories have ensured that 90% of harvested sites are regenerated within 10 years after the timber harvest, ensuring the long-term viability of forests in Canada.

Fire

Fire frequency in Canada's boreal forests decreased from the end of the Little Ice Age, around 1850, until the mid 20th century, in spite of a general warming trend (Flannigan et al., 1998). From 1960 to 1995, the trend was reversed, and fire frequency was 60% greater than during the previous 40 years (1920–1960; Amiro et al., 2001a). On average, 9000 wildfires have burned about 2 million ha of forest annually (data for 1958–2000), with approximately half of this area representing productive forests. However, the total area burned can vary from year to year by a factor of more than 10; this variability was particularly apparent in the 1990s (Amiro et al., 2002). Most fires are less than 10 ha in size, and only 1.5% of all fires are greater than 1000 ha in size. These large fires account for 93% of the total area burned. Approximately 80% of burned forest is considered commercially non-productive. Salvage logging of fire-killed trees in accessible areas is a common forestry operation. Similar to harvested forests, burned forests are usually allowed to regenerate naturally.

Climate Change

Global climate change has the potential to increase fire frequency in Canada's west-central boreal forest since warmer and drier conditions are predicted to occur in that region (Flannigan et al., 1998; Amiro et al., 2001a). There is also a potential for feedback to the atmosphere through this pathway. Already, forest fires in Canada emit on average the equivalent of 18% of current carbon dioxide (CO_2) emissions from the Canadian energy sector, a proportion that reaches 75% in peak fire years (Amiro et al., 2001b).

Impacts of Disturbance on Water Quantity and Regime

Research has demonstrated that the most significant changes in forested watersheds following timber harvest are changes in water table levels, streamflow quantity and regime, water quality, erosion, and sedimentation, and possibly alterations to local groundwater recharge and discharge dynamics. It is likely that similar changes occur after fire. Notably, watershed impacts differ between forestry practices and other land uses, including agriculture and mining.

The hydrologic cycle consists of three major components: precipitation; surface and subsurface water flow and storage; and evaporation from soil, vegetation, lakes, streams, and oceans. The movement of precipitation to ground and surface waters is affected by the amount of forest cover and by forest health and maturity. ET is the process by which water moves through the soil and plants into the atmosphere. In the boreal forest of west-central Canada, a significant portion (66–82%) of the total annual precipitation is returned to the atmosphere as ET (Lieffers and Rothwell, 1986), whereas in wetter areas, including central Quebec, only about one-third of the total annual precipitation is returned to the atmosphere in this form (Guillemette et al., 1999).

The removal of vegetation through timber harvest or destruction by high-intensity wildfire produces short-lived, significant decreases in water losses through ET and decreases in precipitation interception, which together lead to increases in soil water content in disturbed areas. However, local geophysical and climatological characteristics vary throughout Canada's ecozones. Consequently, the effects of timber harvest and fires on streamflow regimes also differ across the country.

Forest cover maintains stability of the infiltration capacity of the soil, decreases runoff, lowers wind speed, and increases precipitation interception, thereby significantly affecting the local microclimate and hydrologic cycle. Conversely, afforestation (the direct conversion by humans of land that has not been forested for a period of at least 50 years to forested land through planting, seeding, or human-induced promotion of natural seeding) affects the local hydrologic cycle by, most prominently, increasing ET, lowering water tables, stabilizing soil infiltration capacities, and decreasing runoff. Although water use by trees is significant, afforestation may reduce local drought conditions under certain circumstances; however, relevant data from Canada are limited (Buttle, 1996). In addition, certain tree species can be used as bioremediators, ameliorating the effects of pollution through a process called phytoremediation. These trees can capture pollutants, thereby removing them from contaminated terrestrial ecosystems and preventing them from reaching aquatic ecosystems (Dietz and Schnoor, 2001).

Canada has a long history of watershed research and monitoring, which has demonstrated how forests can be managed to increase water yield for many needs. Extensive regional and experimental watershed manipulations have been used since the 1960s to investigate the effects of forest management activities on streamflow (Berry, 1991). Such approaches have led to significant increases in our knowledge of the biological and physical processes that regulate watershed hydrology and have contributed to the design and implementation of safer land-use practices. In some areas, scientific findings have been used to guide planning and decision making in the conservation and restoration of riparian forests, wetlands, wildlife habitat, stream habitat, and stream banks, and to minimize the impacts of roads on water quantity and quality. However, in other areas, particularly in the southern boreal forest, construction of roads and railroads has impounded and negatively affected significant areas of riparian forests and wetlands (Poff et al., 1997).

One of the most important results of forestry studies was the realization that production of sediment was linked most strongly to the building and use of forestry roads and to direct perturbations of the stream bank by machinery (Mattice, 1977). Changes in forestry practices have been implemented across Canada to minimize these impacts, including the maintenance of streamside buffer strips and modifications to road-building methods with respect to surface water discharge, culvert placement and sizing, and stream-crossing structures (Ottens and Rudd, 1977). Studies have shown that, when regulations are respected, inputs of sediments into streams because of forest operations are short-lived and often small (Plamondon, 1982). Protection of soils and recovery from logging may be more problematic on steep slopes in areas of high precipitation and low soil stability. However, even in the extreme conditions of the forests on Vancouver Island and the Queen Charlotte Islands, erosion from bare soil was a minor and highly variable contributor to stream sedimentation compared with mass wastage (landslides) from either harvested or unharvested areas (Roberts and Church, 1986; Hetherington, 1992). In both locations, climatic and physical variables had a significant influence on the degree of sediment production and transport into streams.

Effects on Groundwater Recharge-Discharge

Timber harvesting may have both positive and negative impacts on groundwater. An example of the former is the increase in water recharge into groundwater that results from temporary reduction in ET. This effect is likely more significant in dry areas with minimal groundwater recharge under full forest cover. In contrast, the effect is minimal where groundwater recharge is significant. Logging may have a negative effect on local flow of groundwater in steep terrain, where road cuts may intercept lateral drainage and shunt that water into the surface drainage system. This results in loss of water from the drainage system via surface flow and can lead to significant soil erosion. These negative impacts are likely both local and minor (Hetherington, 1992); of more importance in such cases are the potential effects on slope stability.

Changes in Water Table Levels

The boreal zone supports large expanses of forested wetlands because of its relatively flat topography, an abundance of poorly drained surficial deposits and shallow bedrock impervious to water, and a cool and humid climate (Vitt et al., 2000). In these areas, the amount of precipitation and the preharvest position of the water table influence the effect of timber harvesting on the hydrology of the cut-block (an area in which timber is to be or has already been harvested) (Dubé et al., 1995). Depth to the water table is an important, but nonlinear, ecological feature. Frequent rises of the water table to shallow depths may dramatically influence tree growth as well as the trajectory of vegetation dynamics following disturbance.

Water levels are usually high following snowmelt and decrease through the summer when ET is highest. During periods of high rainfall, as well as after snowmelt, the water table is near the soil surface in forested wetlands. The removal of trees decreases ET losses, which results in a less pronounced drop in the water table during periods of low rainfall. Consequently, the difference between seasonal maximum and minimum water levels is less in harvested than in unharvested areas (Dubé et al., 1995). The effects of timber harvest on hydrology are generally restricted to the cut-block itself and do not extend into adjacent uncut tree stands, independent of cut-block position and size. Water tables generally return to natural levels within the first 10 m from the forest edge into the adjacent tree stand (Dubé et al., 1995). The effects of rises in the water table are most severe near the centre of cut-blocks. This suggests lateral water flow from the centre of the cut-blocks toward natural areas bordering the cut-block, creating uneven water table fluctuations throughout the cut-block. Although the effects of water table rises may be ameliorated within short distances into bordering natural tree stands, runoff from cut-blocks may have significant impacts on watershed hydrology.

In conjunction with changes in the water table in cut-blocks, rates of greenhouse gas dynamics in forests may also be affected. For example, well-drained heterogeneous soils have the ability to serve as carbon sinks (Whalen and Reeburgh, 1996). However, timber harvesting has the potential to cause saturation of poorly drained mineral and organic soils, which can then become significant sources of carbon in the form of methane (Roulet and Moore, 1995).

Effects on Streamflow Quantity

By reducing interception of precipitation and ET losses, timber harvesting increases the flow of water out of the watershed. The importance of this effect depends on the ET loss per unit land area, which is a function of water availability, evaporative demand, and, to a lesser extent, vegetation type. Absolute increases in streamflow quantity are larger in warm, wet areas and lower in cool, dry areas. Relative increases in streamflow are larger in dry than in wet areas. Through studies in the eastern, temperate hardwood forest, Hornbeck et al. (1997) found that most of the increases in water yield resulted from increased summer low flows. However, reducing snow interception by harvesting the coniferous cover in the wetter areas of the boreal forest may have a greater effect on annual yield than any reduction in summer flows (Guillemette et al., 1999).

Examples of increases in annual water yield resulting from clear-cutting operations range from 160 mm in Kenora, Ontario (Nicolson et al., 1982), to 349 mm at Carnation Creek on Vancouver Island, British Columbia (Hartman and Scrivener, 1990). Forest perturbations by windthrow and fires at Rawson Lake, Ontario, also increased streamflow by about 170 mm (Schindler et al., 1980). Large fires affect a significant proportion of entire higher-order basins within days. Therefore, the short-term absolute impact of large fires on water yield can be greater than that of gradual harvesting of a basin over many years.

Within a basin, water yield increases are in rough proportion to the area harvested. Buttle and Metcalfe (2000) showed that the effects of various harvesting techniques on stream hydrology were minimal if less than 25% of the area within a watershed was harvested. They attributed this in part to the ability of larger basins to buffer the hydrologic impacts of the relatively small degree of recent forest disturbances. The duration of the effects of tree removal or death on water yield depends on the rate of vegetation regrowth and can range from 7 to 30 years (Swanson and Hillman, 1977).

Effects on Streamflow Regime

Forest removal increases streamflow rates, a beneficial effect for small streams, in which low flow constrains the aquatic ecosystem. Peak flows from snowmelt are the dominant hydrologic feature of most boreal and montane watersheds. Forest harvesting has a direct impact on snowmelt and thus on spring peak flows (Whitaker et al., 2002), but the effect is highly variable (Fig. 1). Peak flows above bankful discharge (the momentary maximum peak flow before a stream overflows its banks onto the floodplain) (1.5-year return period) have been shown to shape stream morphology (Dunne and Leopold, 1978). Results from paired basin studies indicate that snowmelt peak flows above bankful discharge can be increased by up to 50% by removing more than 25% of forest area or volume (Fig. 1). The effect of forest cover removal on peak flow may be amplified if aspect (the angular orientation of the basin with respect to the sun) is uniform throughout the basin. However, the proposed model of peak flow changes for Minnesota (Verry, 1986),

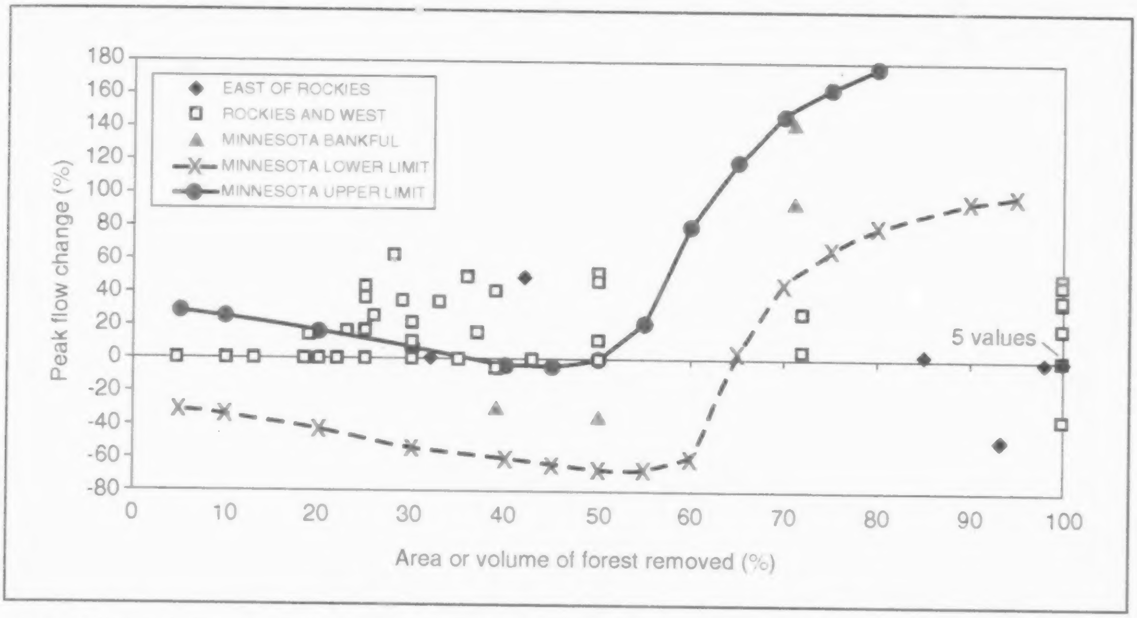

Fig. 1. Changes in snowmelt peak flow above bankful discharge in relation to forest removal by harvesting, fire, or insects in North America. Adapted from Verry (1986) and Plamondon (1993, 2002). The upper and lower limits represent a generalized hypothesis of the impact of snowmelt on peak flow for Minnesota (Verry, 1986).

an area similar to northwestern Ontario, indicates that increases in snowmelt peak flow are likely to occur above 50 to 60% forest removal. Harvesting less than 50% of the basin desynchronizes snowmelt between open and forested areas and tends to decrease peak flows.

Increases in rainfall-induced bankful peak flows are better related to the proportion of forest removal (Fig. 2) than those for snowmelt peak flow. Rainfall peak flow augmentation is caused primarily by an increase in soil water content, which should be well correlated with the percentage of forest removal. Soil disturbances, including roads and skid trails, may increase or decrease peak flow, depending on the time between water pulses generated by the watershed source areas and the disturbed areas. The impact recedes with canopy closure. Also, the impact of harvesting is smaller in hardwood than in coniferous forests because of the smaller interception losses by leafless hardwoods outside of the growing season.

Low flows in summer are generally increased by timber harvest because of rising water tables in response to decreased precipitation interception and decreased ET (Dubé et al., 1995). Summer rainfall may produce small to moderate increases in storm and peak flows in harvested areas relative to forested basins (Pomeroy et al., 1997) because of the generally wetter soils in harvested areas (as a result of decreased ET); therefore, the potential for streamside soil saturation and streamflow generation may be increased.

Although the impact of increased streamflow may be significant on primary streams, the cumulative effect on secondary and tertiary streams may be negligible. In addition, because of the overall small impact at the watershed scale, the potential impact of forestry on downstream flooding may be small (Martin et al., 2000). This situation is quite different from land-use changes that cause a permanent change in the ecosystem. For example, permanent conversion of forest cover over 27% of the 95,000 km^2 drainage basin above St. Paul, Minnesota, increased annual flood peaks by 43% (Miller and Frink, 1982).

The removal of riparian trees and road-building can have potential impacts on stream biota. Depending on the situation, logging can have positive or negative effects on stream morphology and fish habitat (Ralph et al., 1994). Even partial removal of riparian vegetation can cause elevation of water temperatures and can increase the exposure of the stream to ultraviolet (UV) radiation. Elevated temperatures and increased UV radiation cause changes in stream invertebrate communities (Kelly et al., 2003) and, in conjunction with increased nutrients from timber harvesting, undesirable algal growth. Inadequately installed culverts on logging roads often block the passage of fish, either by creating jumps that are too high or water velocities that are too great to overcome.

The effects of harvesting or fires on lake and stream properties are often difficult to separate from those of climate, even in well-designed studies with control basins (Schindler et al., 1996; Steedman and Kushneriuk, 2000). Removal of the riparian trees around small lakes by either natural disturbances or harvesting increases

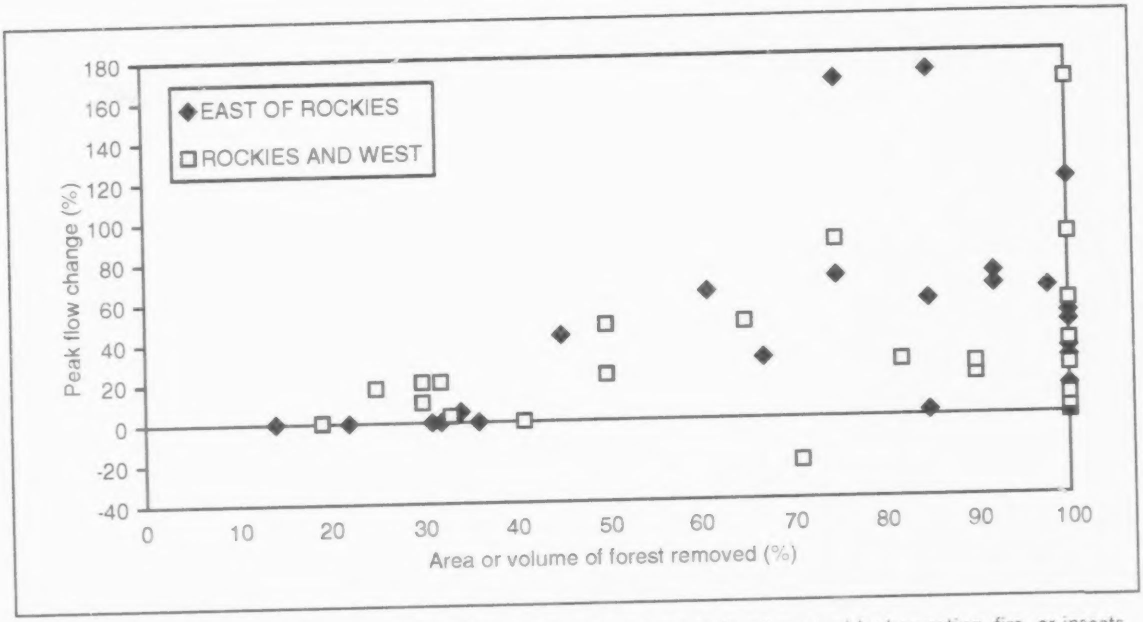

Fig. 2. Changes in rainfall peak flow above bankful discharge in relation to forest removal by harvesting, fire, or insects in North America. Adapted from Plamondon (1993, 2002).

over-water wind speeds and either increases (France, 1997) or decreases (Steedman and Kushneriuk, 2000) the depth of the thermocline. Maintenance of buffer strips prevents the increase in over-water wind speed (Steedman and Kushneriuk, 2000). Schindler et al. (1996) reported an increase in lake water clarity following fires during a dry period with reduced precipitation and streamflow to lakes. Steedman and Kushneriuk (2000) reported the contrary, a decrease in water clarity following harvesting, but stated that the effects could have been related to climate.

Increased sediment yields to lakes as a result of fires or harvesting have the potential to silt spawning beds and disturb the habitats of fish and other freshwater organisms (Beaty, 1994). These problems point to the need for the maintenance and reinforcement of measures to prevent erosion and sedimentation during harvesting. However, there are as yet no hard and fast rules to determine threshold levels of erosion and siltation with respect to fish populations. For example, Gunn and Sein (2000) found that lake trout populations were insensitive to a major reduction in spawning habitat through simulated siltation, but they were severely affected by road access and ensuing fishing pressure. Murphy et al. (1986) showed that adequate buffer strips maintained or enhanced fish habitat and productivity, while removal of buffer strips had a negative impact on these variables. Changes in water flow patterns in harvested areas above a buffer strip can also affect trout spawning beds (Curry and Devito, 1996), although it seems that no direct experimental evidence exists on the magnitude of the effects on trout spawning success.

Changes in Land Use

Human settlement in Canada has resulted in large-scale conversions of forests to urban and agricultural land uses. The changes in the natural components of the hydrologic cycle brought about by these land-use changes have had large impacts on water quantity, water quality, and the timing of flow events. As a result of these changes, there is lingering confusion between the impacts of forest harvesting and those of land-use changes on water resources. Hydrologic research across Canada and around the world has shown the importance of forest and other wildlands in the regulation of streamflow and the maintenance of water quality. As a general rule, harvesting impacts on streamflow regime and water quality are usually short-lived and less severe than those brought about by land-use changes, provided that forest soils are protected and vegetation recovery is rapid.

Knowledge and Program Needs

There is an increasing demand for forests to provide clean water for a multiplicity of purposes, including fisheries, agriculture, and recreation. It is imperative to continue research to address existing and emerging issues as they pertain to the quantity as well as the quality of freshwater resources in Canada. Improved knowledge and understanding of forest-water relationships are needed to integrate water issues into forestry and related decision-making systems and to support water quantity and quality criteria in support of sustainable forest management practices.

In 2001, the Canadian Forest Service carried out a scoping exercise to identify research opportunities in forest hydrology (Beall et al., 2001). A number of broad research elements were identified and grouped into three research themes pertaining to freshwater availability. Priorities have not been established, nor has the linkage with respect to currently available information been fully carried out. However, the themes and results from that exercise are pertinent to the current exercise and are presented here:

- Effects of forest condition, natural disturbance, and forest management activities:
  - effects of harvesting on water quantity
  - effects of wildfire, insect outbreaks, and forest condition (e.g., regenerating versus old growth) on water quantity
  - effects of intensive forest management on surface and ground water supplies
  - development of forest management practices to preserve or enhance water supply, and
  - effects of forest management and disturbances on forest aquatic ecosystem habitat, productivity, and diversity.
- Climate variability and climate change effects:
  - effects of climate variability and climate change on forest hydrologic cycles
  - impacts on water supply from forested areas (timing and quantity), and
  - impacts on ecological integrity of aquatic ecosystems.
- Synthesis and integration:
  - development and adaptation of large-basin and national process and empirical models, which integrate hydrologic and biogeochemical cycles to improve prediction capabilities and provide decision support
  - retrieval, assessment, and archiving of long-term data sets for development and validation of models and development of a national database
  - scaling up of plot-based and patch-based results to landscape and regional scales
  - scaling down regional climate models to provide realistic scenarios for input to process models, and
  - determination of socioeconomic costs and benefits resulting from altered forest hydrologic regimes due to anthropogenic and natural disturbances.

The significant variability in harvesting and site preparation perturbations and in wildfire intensity in watersheds, as well as the variability in Canada's ecozones has resulted in a large variance in the responses of individual nutrients and elements to natural and anthropogenic disturbances. Most watershed studies have been conducted near the southern extent of the boreal forest, and most of those were performed in central and eastern Canada (Ontario and Quebec). The relevance of results from eastern Canada to other areas of Canada, where different physiographic and soil conditions prevail, remains unclear and warrants further investigation (Buttle et al., 2000). Although hydrologic research has increased over the past 3 to 5 years in Canada, the results of these studies have not been widely disseminated or are still being worked up. Hence, many forest managers must fall back on studies from smaller scales and from forest environments that are not necessarily directly relevant to the Canadian context (J.M. Buttle, pers. comm.).

References

Amiro, B.D. 2001. Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. Glob. Change Biol. 7: 253-268.

Amiro, B.D., M.D. Flannigan, B.J. Stocks and B.M. Wotton. 2002. Perspectives on carbon emissions from Canadian forest fires. For. Chron. 78: 388-390.

Amiro, B.D., J.I. MacPherson and R.L. Desjardins. 1999. BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes. Agric. For. Meteorol. 96: 199-208.

Amiro, B.D., B.J. Stocks, M.E. Alexander, M.D. Flannigan and B.M. Wotton. 2001a. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire 10: 405-413.

Amiro, B.D., J.B. Todd, B.M. Wotton, K.A. Logan, M.D. Flannigan, B.J. Stocks, J.A. Mason, D.L. Martell and K.G. Hirsch. 2001b. Direct carbon emissions from Canadian forest fires, 1959-1999. Can. J. For. Res. 31: 512-525.

Bayley, S.E., D.W. Schindler, K.G. Beaty, B.R. Parker and M.P. Stainton. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Can. J. Fish. Aquat. Sci. 49: 584-596.

Beall, F., R. Stewart, I. Campbell, C. Campbell, H. Hirvonen and P. Bernier. 2001. Forest water resources – CFS scoping paper. Nat. Res. Can., Can. For. Serv., Ottawa, Ont., Canada.

Beaty, K.G. 1994. Sediment transport in a small stream following two successive forest fires. Can. J. Fish. Aquat. Sci. 51: 2723-2733.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Berry, G.J. 1991. Hydrology of drained and undrained black spruce peatlands: streamflow and hydrologic balance. Forest Information Systems Ltd., Victoria, B.C., Canada. COFRDA Rep. 3317.

Buttle, J.M. 1996. Identifying hydrological responses to basin restoration: an example from southern Ontario. *In* McDonnell, J.J., J.B. Stribling, L.R. Neville and D.J. Leopold (ed.), Watershed restoration management: physical, chemical, and biological considerations. Amer. Water Res. Assoc., Herndon, Va., U.S.A. TPS-96-1.

Buttle, J.M., I.F. Creed and J.W. Pomeroy. 2000. Advances in Canadian forest hydrology, 1995-1998. Hydrolog. Process. 14: 1551-1578.

Buttle, J.M. and R.A. Metcalfe. 2000. Boreal forest disturbance and streamflow response, northeastern Ontario. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 5-18.

CCFM (Canadian Council of Forest Ministers). 2002. Compendium of Canadian forestry statistics. Natural Resources Canada, Ottawa, Ont., Canada.

CFS (Canadian Forest Service). 2002. 2000-2001 The state of Canada's forests. Sustainable forestry – a reality in Canada. Nat. Res. Can., Can. For. Serv., Ottawa, Ont., Canada.

Curry, R.A. and K. Devito. 1996. Hydrogeology of brook trout (*Salvelinus fontinalis*) spawning and incubation habitats: implications for forestry and land use development. Can. J. For. Res. 26: 767-772.

Dietz, A.C. and J.L. Schnoor. 2001. Advances in phytoremediation. Environ. Health Perspect. 109(Suppl. 1): 163-168.

Dubé, S., A.P. Plamondon and R.L. Rothwell. 1995. Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland. Water Resour. Res. 31: 1741-1750.

Dunne, Y. and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman & Co., San Francisco, Ca., U.S.A.

EC (Environment Canada). 2003. Freshwater Website. Environment Canada, Ottawa, Ont., Canada. Available from: http://www.ec.gc.ca/water/e_main.html; Internet. Cited 15 September 2003.

Flannigan, M.D., Y. Bergeron, O. Engelmark and B.M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. J. Veg. Sci. 9: 469-476.

France, R. 1997. Land-water linkages: influence of riparian deforestation on lake thermocline depth and possible consequences for cold stenotherms. Can. J. Fish. Aquat. Sci. 54: 1299-1305.

Guillemette, F., A.P. Plamondon and D. Levesque. 1999. Effets de la coupe sur le bilan hydrologique. Bassin expérimental du ruisseau des Eaux-Volées (BEREV). Département des sciences du bois et de la forêt. Université Laval, Québec, Canada.

Gunn, J.M. and R. Sein. 2000. Effects of forestry roads on reproductive habitat and exploitation of lake trout *(Salvelinus namaycush)* in three experimental lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 97-104.

Hartman, G.F. and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Can. Bull. Fish. Aquat. Sci., No. 223.

Hetherington, E.D. 1992. Watershed hydrology, p. 33-47. *In* Hogan, D.L., P.J. Tschaplinski and S. Chatwin (ed.), Carnation Creek and the Queen Charlotte Islands fish/forestry workshop: applying 20 years of coast research to management solutions. B.C. Min. For. Res. Program, Victoria, B.C., Canada.

Hornbeck, J.W., C.W. Martin and C. Eagar. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. Can. J. For. Res. 27: 2043-2052.

Kelly, D.J., M.L. Bothwell and D.W. Schindler. 2003. Effects of solar radiation on stream benthic communities: an intersite comparison. Ecology 84: 2724-2740.

Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. J. Biogeogr. 24: 663-674.

Larsen, C.P.S. and G.M. MacDonald. 1998. An 840-year record of fire and vegetation in a boreal white spruce forest. Ecology 79: 106-118.

Lieffers, V.J. and R.L. Rothwell. 1986. Effects of depth of water table and substrate temperature on root and top growth of *Picea mariana* and *Larix laricina* seedlings. Can. J. For. Res. 16: 1201-1206.

Martin, C.W., J.W. Hornbeck, G.E. Likens and D.C. Buso. 2000. Impact of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 19-29.

Mattice, C.R. 1977. Forest road erosion in northern Ontario: a preliminary analysis. Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont., Canada. Inf. Rep. O-X-254.

Miller, J. and D.L. Frink. 1982. Changes in flood response in the Red River of the North Basin, North Dakota-Minnesota. U.S. Geol. Surv., Bismarck, N.D., U.S.A. Open File Rep. 82-774.

Murphy, M.L., J. Heifetz, S.W. Johnson, K.V. Koski and J.F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Can. J. Fish. Aquat. Sci. 43: 1521-1533.

Nicolson, J.A., N.W. Foster and I.K. Morrison. 1982. Forest harvesting effects on water quality and nutrient status in the boreal forest, p. 71-89. *In* Steed, G.L. and H.R. Hudson (ed.), Proc. Can. Hydrol. Symp. '82 – Hydrologic processes of forested areas. Nat. Res. Counc. Can., Ottawa, Ont., Canada.

Ottens, J. and J. Rudd. 1977. Environmental protection costs in logging road design and construction to prevent increased sedimentation in the Carnation Creek watershed (Vancouver Island). Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C., Canada. Inf. Rep. BC-X-155.

Plamondon, A.P. 1982. Augmentation de la concentration des sédiments en suspension suite a l'exploitation forestière et durée de l'effet. Can. J. For. Res. 13: 883-892.

Plamondon, A.P. 1993. Influence des coupes forestières sur le régime d'écoulement de l'eau et sa qualité. Centre de recherche en biologie forestière, Université Laval et Ministère des forêts, Québec, Canada. 179 p.

Plamondon, A.P. 2002. La récolte forestière et les débits de pointe : État des connaissances sur la prévision des augmentations des pointes, le concept de l'aire équivalente de coupe acceptable et les taux régressifs des effets de la coupe sur les débits de pointe. Direction de l'environnement forestier, Ministère des ressources naturelles, Québec, Canada.

Poff, L.N., J.D. Allen, M.B. Bain, J.R. Kerr, K.L. Prestegaard, B.D. Richter, R.E. Sparka and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47: 769-784.

Pomeroy, J.W., R.J. Granger, A. Pietroniro, J.E. Elliot, B. Toth and N. Hedstrom. 1997. Hydrologic pathways in the Prince Albert Model Forest. Final report to the Prince Albert Model Forest Association, Nat. Hydrol. Res. Inst., Environ. Can., Saskatoon, Sask., Canada.

Ralph, S.C., G.C. Poole, L.L. Conquest and R.J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. 51: 37-51.

Roberts, R.G. and M. Church. 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Can. J. For. Res. 16: 1092-1106.

Roulet, N.T. and T.R. Moore. 1995. The effect of forestry drainage practices on the emission of methane from northern peatlands. Can. J. For. Res. 25: 491-499.

Schindler, D.W., S.E. Bayley, B.R. Parker, K.G. Beaty, D.R. Cruikshank, E.J. Fee, E.U. Schindler and M.P. Stainton. 1996. The effects of climate warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol. Oceanogr. 41: 1004-1017.

Schindler, D.W., R.W. Newbury, K.G. Beaty, J. Prokopowich, T. Ruszczynski and J.A. Dalton. 1980. Effects of windstorms and forest fire on chemical losses from forested watersheds and on the quality of receiving stream. Can. J. Fish. Aquat. Sci. 37: 328-334.

Steedman, R.J. and R.S. Kushneriuk. 2000. Effects of experimental clearcut logging on thermal stratification, dissolved oxygen, and lake trout *(Salvelinus namaycush)* habitat volume in three small boreal forest lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 82-91.

Stocks, B.J., J.A. Mason, J.B. Todd, E.M. Bosch, B.M. Wotton, B.D. Amiro, M.D. Flannigan, K.G. Hirsch, K.A. Logan, D.L. Martell and W.R. Skinner. 2002. Large forest fires in Canada, 1959-1997. J. Geophys. Res. 108: FFR5-1-FFR5-12.

Swanson, R.H. and G.R. Hillman. 1977. Predicted increased water yield after clear-cutting verified in west-central Alberta. Can. For. Serv., North. For. Res. Cent., Edmonton, Alta., Canada. Inf. Rep. NOR-X-198.

Verry, E.S. 1986. Forest harvesting and water: the lake states experience. Water Resour. Bull. 22: 1039-1047.

Vitt, D.H., L.A. Halsey, I.E. Bauer and C. Campbell. 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Can. J. Earth Sci. 37: 683-693.

Whalen, S.C. and W.S. Reeburgh. 1996. Moisture and temperature sensitivity of CH_4 oxidation in boreal soils. Soil Biol. Biochem. 28: 1271-1281.

Whitaker, A., Y. Alila, J. Beckers and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resour. Res. 38: 1172.

Chapter 9

LAND-USE PRACTICES AND CHANGES – MINING AND PETROLEUM PRODUCTION

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Introduction

The extraction of non-renewable resources, including metals, crude oil, natural gas, coal, fertilizers and building aggregate, is essential to our present standard of living. It produces many of the constituents used in homes, offices, automobiles, and provides products for heating and fuel. Although overall impacts may be lower than those of other land uses, such as agriculture and municipalities, mining and petroleum production can have a significant impact locally on water availability for other uses. Large volumes of water are used by the mining and petroleum sectors for extraction and concentration of metals and non-metal minerals, extraction of light and heavy crude, and generating electricity required for crushing ore, on-site processing, smelting, refining and other aspects of treating resources to improve their properties (Environment Canada, 2002; Table 1).

To gain access to minerals, metal and non-metal mines are dewatered using pumping wells, diversion techniques and near-horizontal drainage passages (adits) (see Fig. 1 and 2). Water is used to process ore at the mine site after it is extracted. This water is often recirculated, and as a result many mines are able to minimize water discharge during operation. This is reflected in water use surveys carried out by Environment Canada. Waters are primarily (78%) discharged to freshwater bodies and undergo little beyond primary treatment (Environment Canada, 2002). After ore recovery is complete, previously drained underground workings and open pits refill, further diverting ground and surface water flows. Precise estimates of water intake and discharge associated with mining activities are difficult to obtain because of uncertainties associated with evaporative losses, and gains and losses through subsurface flow during both the active and inactive stages of mining.

In the production of petroleum and natural gas, water is used as make-up fluid to maintain pore pressures, for formation flooding to enhance recovery of crude oil, to extract crude oil from oilsand deposits, and for dewatering of coal formations to enhance methane recovery. Much of the make-up water injected for crude oil production is diverted from surface waters or obtained from shallow, fresh groundwater supplies. This water is injected into deep formations and is lost for future use. The large volumes of water consumed in processing oilsands are retained for several decades in the pore space of waste tailings, and are also not readily available for further use. The volume of water extracted for coalbed methane production can be very large, and requires quantification.

Very large volumes of wastes are produced by the mineral and petroleum extraction industries. Precipitation waters infiltrating these wastes can become highly contaminated. Degradation of water quality continues for decades or centuries after resource recovery is complete. At this time, there is no accepted methodology for estimating the value of the lost use of water due to these long-term adverse changes in water quality.

In Canada, statistics on water use by the mineral and petroleum extraction industries have the greatest uncertainty of all major industries surveyed (Environment Canada, 2002). These surveys focus on active operations in Canada. In the mineral extraction industry, the primary threat posed to freshwater availability, however, is the release of water of substandard quality long after ore extraction is complete. The water that has been sufficiently altered to limit further reuse requires quantification. In the petroleum extraction industry, the volume of water degraded as the result of legacy activities may also represent a large volume of water requiring quantification.

Threats to Water Availability in Mineral and Petroleum Extraction

Metal-Mining Sector

Although the area of immediate disturbance is relatively small, metallic and non-metallic mining can dramatically alter the local landscape, producing large stockpiles of broken and ground rock. Mines in Canada range

Table 1. Survey of water use in the mineral extraction and associated manufacturing industries (million cubic metres water/year), 1996 (Environment Canada, 2002)

Activity	Intake	Recycle*	Gross Water Use	Discharge	Consumption**
Mineral Extraction					
Metal mines	427.8	260	1542	573.6	NA
Non-metal mines	56.3	72	97	72.4	NA
Coal mines	34.2	124	77	25.9	NA
Mineral Manufacturing					
Primary metals	1423.0	1447.9	2870.9	1303.0	120.0
Non-metallic mineral products	102.3	91.8	194.1	83.1	19.2
Petroleum and coal products	370.5	541.4	911.9	348.0	22.5

* Recycle rate = recycle as a % of intake.

** No reliable mining water consumption values can be estimated due to a high level of discrepancies between intake and discharge, probably due to unaccounted for tailings pond losses to evaporation and subsurface seep age.

from small to large operations occupying several square kilometres. These mines produce metals such as copper, gold, iron, nickel, silver, and zinc. Some mines have been abandoned over 100 years ago, while others have been abandoned more recently. A metal mine is both a resource recovery operation and a waste disposal site. Often more than 90% of the excavated rock, and sometimes in excess of 99%, is left on site, and only the remainder taken off-site as products.

Metal-bearing rock is excavated from open pits and underground workings. Most mines require dewatering through pumping, diversion or other means (Table 1). Large drawdown cones, conical depressions in the groundwater table, can be created in the vicinity of the mine (Fig. 1). Drainage adits and diversions are used to drain and/or prevent inflow of water into workings and limit drainage through mine wastes (Fig. 2). Drawing down the water table and diverting runoff to other watersheds may significantly reduce the volume of water available for other uses (e.g., fisheries) if water use is large enough (e.g., the Kemano Diversion associated with the Kitimat Smelter, British Columbia; see also Chapter 1) or if the mine occupies the headwaters of a small watershed (e.g., Mt. Polley Mine, British Columbia). In regions such as the Northwest Territories and parts of Ontario and Quebec, dewatering of deep mines can result in the extraction of saline waters and discharge of this water at the surface.

After mining is complete, dewatering ceases and surface and ground water flows into pits and underground workings (Fig. 1). Mine reflooding takes place over a few years (Levy et al., 1997) to many decades (Davis and Ashenberg, 1989), depending on the original groundwater drawdown, the availability of precipitation and surface water, and the physical properties of the surrounding geological materials. Site-specific information is required to make an accurate assessment of post-operational water intake.

Mines produce two main waste products: waste rock and tailings. Waste rock is coarse to fine-crushed rock originally excavated to gain access to the ore, but with insufficient metal value for processing to be economical. Waste rock is usually disposed in piles, but is also used in the construction of roads and containment berms or back-filled into unused workings. Tailings are the finely ground residue derived from processing the ore. Tailings slurries are disposed to impoundments or back-filled into underground workings. Daily production of waste rock in Canada is estimated to be 1,000,000 tonnes, and daily production of tailings is estimated to be 950,000 tonnes (Government of Canada, 1991). The waste stockpiles of large mines are among the largest man-made structures in the world (ICOLD, 1996).

Mining exposes underground workings, open pit walls, talus, waste rock and tailings to atmospheric oxygen. The exposure of sulphide minerals contained in the host rock and mine wastes to oxygen may release acid and Al, As, Cd, Co, Cu, Fe, Hg, Mn, Ni, Pb, Se, and Zn to surrounding waters (see photograph). Low-quality water can occur in pit lakes (Miller et al., 1996; Levy et al., 1997; Morin and Hutt, 1997; Eary, 1999; Shevenell et al., 1999; Ramstedt et al., 2003), underground workings (Morin and Hutt, 1997; Nordstrom and Alpers, 1999; Nordstrom et al., 2000), groundwater flow systems adjacent to mines (Blowes and Jambor, 1990; Blowes et al., 1991; Miller et al., 1996; Morin and Hutt, 1997; Johnson et al., 2000; Moncur et al., 2003) and surface water bodies (see photograph) (Morin and Hutt, 1997; Nordstrom and Alpers, 1999; Moncur et al., 2003). Most metal and some coal mines contain elevated concentrations of sulphide minerals and have the potential to produce low-quality drainage (Blowes and Jambor, 1990; Blowes et al., 1991; Morin and Hutt, 1997; Price and Errington, 1998, Price and Hart, 1999). Other threats to water quality include milling reagents, such as cyanide used in the extraction of gold, and blasting residues. Mine workings and wastes can produce low-quality drainage for decades to centuries after ore extraction is completed (Coggans et al., 1998; Nordstrom and Alpers, 1999; Wireman, 2002; Moncur et al., 2003).

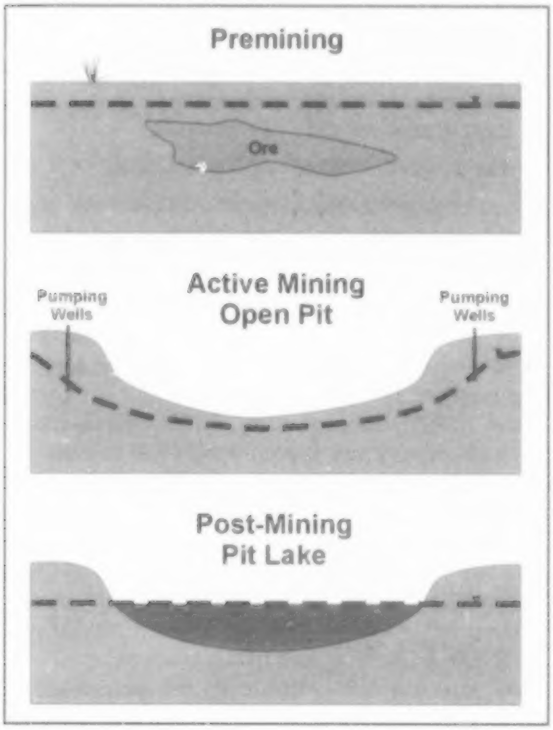

Fig. 1. Schematic diagram showing influence of mining activities on groundwater table during premining, active mining and post-mining stages. The water table is lowered during active mining stages and then is allowed to recover as the mine refloods. Mine reflooding can take years to decades after ore extraction ceases. Water consumed for dewatering can be used in mine and mill operations or discharged. Water used for reflooding is not usually accounted for in water consumption surveys.

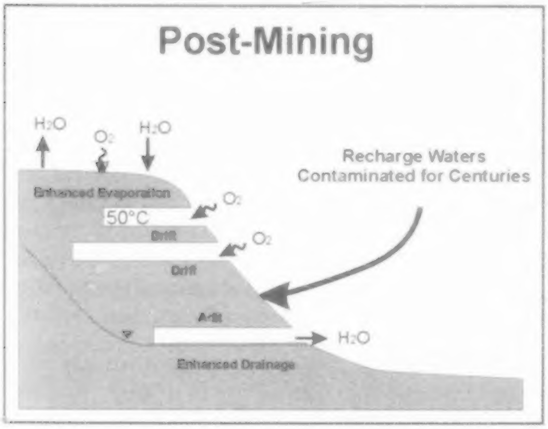

Fig. 2. Schematic diagram showing mine workings and drainage adits used to lower water table. Increased drainage from workings and adits typically results in a permanent depression in the water table.

Surface water discharge during active stages of metal mine operations, and for the first few years after cessation of mining activities, must meet federal water quality regulations. Provincial discharge limits exist as long as there is a risk of significant contaminant release, which is often indefinitely where there is a potential for significant metal leaching or acidic drainage. In British Columbia, surface water discharge limits, along with mitigation, maintenance, reclamation and monitoring requirements may be set for every stage of the mine life (Price, 1999). Release of deleterious substances to surface waters supporting fish habitat is regulated through the federal *Fisheries Act*.

In Canada, there are a number of old mines that continue to release deleterious substances to surface and ground water, such as mines at Kam Kotia (Ontario), Britannia (British Columbia), and Sherridon (Manitoba). Modern mines have expensive programs to prevent impacts during operation. Capital costs for water treatment often exceed tens of millions of dollars, with post-closure operating costs in the order of $1 million per year and total costs that may exceed $100 million (Price and Bellefontaine, 2002).

There is no accurate information on the volume of contaminated effluent released to the subsurface and surface water bodies by mines in Canada or other parts of the world. However, the largest source of impacts to water resources appears to be older, abandoned mines. In the United States, there are between 20,000 and 50,000 largely abandoned mines releasing acidic, metal-rich drainage on U.S. Forest Service Lands (USDA, 1993). Over 4000 miles of rivers and streams in the eastern United States and between 5000 and 10,000 miles of streams in the western United States have been adversely affected by mine drainage water (Kleinmann, 1990; USDA, 1993). In Canada, there are approximately 10,000 inactive mines, with no accurate information on the total number, size, and impacts on water quantity and quality.

Most mines are located in less populated areas of the country, where the primary competing water use is fish and wildlife habitat. In wetter regions, the availability of a reliable supply of freshwater is not limiting. However, avoidance of impacts to fisheries and other water users can greatly increase mining costs, e.g., Kemess Mine, British Columbia, and may prohibit mining. Even though most mining occurs in areas of low population density, there may be impacts on treaty rights of First Nations (e.g., at Rae Rock, Northwest Territories) or other priority commitments of the governments, such as provincial parklands (e.g., dewatering of the proposed Aquarius Project near Nighthawk Lake, Ontario). In some areas, mining has occurred near a local population centre that now needs to address the physical and chemical legacy of past mining activities and public safety.

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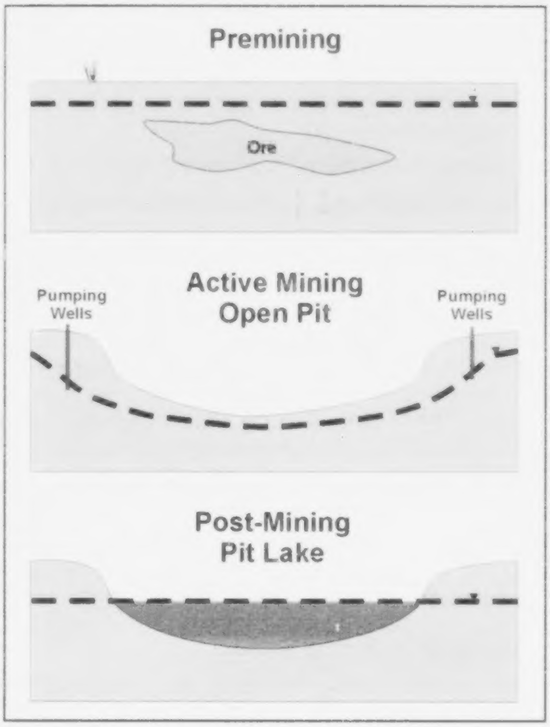

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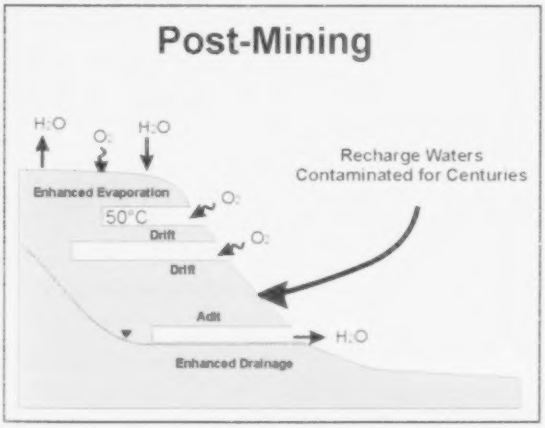

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A variety of mitigation measures have been proposed to limit the environmental impacts from sulphide oxidation (Blowes et al., 1994; Feasby et al., 1991; Feasby and Tremblay, 1995; Price and Errington, 1998). The techniques most commonly employed in Canada are chemical treatment of drainage, flooding mine wastes to create a water cover and dry covers. Chemical treatment is very effective in removing metals from surface drainage, but due to on-site impacts, sludge disposal and high costs, it tends to be a strategy of last resort. Flooding in a constructed impoundment, old mine workings, or natural water bodies can be very effective in limiting the oxidation of fresh reactive wastes (Vigneault et al., 2001; Price, 2001). Flooding requires continued availability of water in perpetuity. Soil and other engineered cover technologies have been proposed to reduce water and oxygen inputs to mining wastes. As an example, in British Columbia there are at least thirteen major mines that are or will be using chemical drainage treatment, twenty-four sites that use or will use water covers to prevent environmental impacts and nine sites that use or are proposing to use dry covers (Price and Bellefontaine, 2002).

Other practices that have been shown to be beneficial in the mitigation of metal leaching associated with sulphide oxidation include:

- avoidance of problematic materials
- waste segregation
- diversion of upstream drainage
- lime amendments during processing
- mine processing changes
- selective timing of drainage discharge
- blending of waste materials to create a benign composite
- locating facilities to allow drainage collection
- minimizing leaching and maximizing natural dilution and attenuation, and
- non-chemical forms of drainage treatment.

Low-quality drainage emanating from the Sherridon mine in northern Manitoba. At this site the wastes and workings have oxidized for over 70 years leading to the release of elevated concentrations of sulphide oxidation products to surface waters. The water quality is severely degraded in four lakes surrounding the mine. In the absence of an effective remedial program, low-quality drainage will continue to be generated for centuries. The volume of water impacted is many times the original volume of water consumed during the active stages of mining, suggesting that water audits for the mining industry require inclusion of consumption rates during both active and inactive stages of mining.

Often, sites use a combination of different mitigation strategies, either for the purpose of primary protection or for contingency reasons. Many of the techniques require water use, diversion and discharge for long periods after ore extraction has been terminated.

Refineries and smelters that process mine concentrates, use large volumes of water for processing and cooling (Table 1). Plant discharge water and drainage infiltrating through refinery and smelter wastes can become contaminated. Because smelting and refining processes are dealing with concentrates, it is common for metals to be much more concentrated in these waste streams, perhaps creating an elevated potential for adverse water-quality impacts per unit mass or volume.

Non-metallic Mining Sector

Non-metallic mining, including the production of potash and phosphate fertilizers, uranium, crushed sand and gravel aggregate, coal, salt, dimension stone, gypsum, and more recently diamonds, has water requirements. If these operations require water and are located in the semi-arid west, water availability for mine activities can be limiting. This is the case at several potash mines in the Prairies.

Production of potash typically includes a separation process involving pumping groundwater or diverting surface water. Water is lost to evaporation, and in some instances through deep-well injection, or subsurface recharge. The water demands required for potash production need to be balanced with competing uses in the region.

Coal processing requires water and, although less commonly than metal mines, coal wastes and workings may be a potential source of metal and metalloid leaching and acidic drainage. Water use and power generation and the industrial use of coal is covered in Chapters 2 and 5 of this volume.

Water use is more limited in construction aggregate mining compared to other forms of mining. However, these operations may draw down the water table locally, and often require erosion control and sediment retention measures to provide acceptable drainage for discharge.

Open-pit and underground extraction of kimberlite ore for diamonds has recently begun in Canada at the Lac de Gras, Northwest Territories. Dewatering of these mines can result in the extraction of deep saline waters, and low-quality drainage can be generated from waste rock if active water management is not used (Baker et al., 2003). The shortage of water in this region introduces higher treatment costs to maintain effluent concentrations at acceptable levels.

Oil and Gas Extraction Sector

Large volumes of water are used for the extraction of oil and gas (Table 1), and much of the water consumed is not available for reuse. Water is primarily used for:

- fluid make-up to maintain formation pressures for production of light crude
- tertiary recovery methods
- extracting heavy crude from oilsands, and
- coalbed methane extraction.

For the extraction of light crude, both oil and water are pumped to the surface, resulting in a decline in formation pressures. To counteract this decline in pressure, fluid (fresh, brackish, saline or recycled water, or carbon dioxide), is injected downhole. When a well first starts production, the percent of oil recovery can be high, requiring large volumes of fluid for injection to replace or supplement the original formation of oil and water. As the recovery of oil declines, the need for supplemental make-up fluid may also decline. Tertiary methods used for enhanced oil recovery may also require water. Tertiary methods can involve overpressurization techniques, and injection of surfactant solutions, steam and other fluids. If freshwater is consumed for these activities, it usually becomes highly contaminated and is not available for future reuse.

Steam from surface and ground water is used to extract oil from oilsand deposits. Approximately three barrels of water are used to extract one barrel of oil. Reuse of water consumed in oilsand processing is limited due to long drainage times from containment facilities and high treatment costs to return the affected water to unrestricted use. Due to the relatively new development of waste containment facilities in the oilsand industry, the volume and quality of contaminated effluent that will discharge is not well known.

Coalbed methane production requires dewatering large volumes of rock to increase extraction of methane. This water can be low in quality, ranging from substandard to brackish. The dewatering activities can lead to declines in surface water levels in adjoining water bodies.

In humid regions of Canada, petroleum extraction activities typically are not limited by water availability. Effects of water consumption are usually local. Changes in water quality are of primary concern. In contrast, the semi-arid and arid regions of the Prairies face increasingly significant water shortages due to intensification of petroleum production, agriculture and urbanization. For example, the oil and gas industry in Alberta has the rights to 25% of the province's groundwater supply for use in recovering oil from wells.

Extraction of oil and gas can also lead to the degradation of groundwater in shallow aquifers from leaks around well casings and pipelines, and shallow disposal of saline formation waters. Considering the large numbers of wells and pipelines in certain regions, these effects can expand from local to regional in scale.

Trends

It now is widely accepted that the surface of earth has warmed and will continue to do so for decades more. Global climatic change may have major implications, not all of them obvious, for water balances on regional scales at mid- to upper latitudes. For example, detailed re-evaluations of world-wide data from the past 50 years have identified statistically significant decreases in pan-evaporation rates at the same time that average surface temperatures have increased (Roderick and Farquhar, 2002). Predictions of the role of climate change on water quantity and quality issues associated with mineral and petroleum extraction are an essential aspect of long-term water management. It is, however, important to stress that there is a need to assess trends in water use for these sectors under current climatic conditions, in addition to evaluating these trends under changing climatic conditions.

Metal and Non-metallic Mining Sector

The quantity of water used for the development and operation of active metal mines has increased slightly over the past several decades (Environment Canada, 2002). At inactive mines, water intake statistics are not generally available. Water is consumed for mine reflooding and to maintain management systems, such as water covers. Water discharge statistics also are not available. Contaminated water can be discharged from drainage channels, underground workings, tailings impoundments, waste rock piles, and refinery waste impoundments. Discharge, with or without mitigation, can be directly to surface water bodies, or to the subsurface.

In Canada, the number and size of mines have increased substantially since the 1940s. Peak concentrations of contaminants discharged from mine sites may occur many years after the onset of mining. This delay of contaminant release arises because of delays in mine flooding, temporary acid neutralization and contaminant attenuation, and long groundwater transport times. Because the total volume of mine wastes and total number of mines are growing, it can be expected that there will be an increase in the potential for contamination. An increase in the volume of water required for site management activities (vegetation programs, water covers, dilution of discharge waters) is also expected.

Preventing future degradation of water quality often requires mitigation facilities capable of functioning across both normal climatic ranges, but also after extreme climatic events. For example, accurate predictions of the frequency and duration of drought conditions are required to ensure adequate water for flooding or dilution, sustaining revegetation and the design of oxygen-impeding soil covers, and preventing windblown tailings. Flood prediction is required in the design of retaining dams, collection and treatment systems, diversion structures, and water covers. Assignment of design flood magnitudes is hampered in most mining districts due to a lack of long-term temperature, snow course, precipitation and hydrological data from which predictive calculations can be made.

Dilution is a common component of drainage management at Canadian mine sites. Measures to direct flow through permanent water diversions may by themselves be sufficient to prevent impacts to other aquatic resources, but such measures need careful consideration. With more and more stringent surface water quality guidelines and regulations in place, however, dilution is often not sufficient. For example, when other demands are being placed on the water flows, and when flows decline due to climatic variations, there may be insufficient water available to meet water quality guidelines.

At many mines, emphasis is placed on preventing oxidation of sulphide-rich mine wastes with water covers. In these systems, the wastes are covered with water to limit oxidation and release of metals. For example, in British Columbia, there are presently ten tailings disposal facilities which rely on water covers to prevent sulphide oxidation reactions. The long-term success of these managed waste facilities requires a favourable water balance and active engineering management (Yanful and Verma, 1999; Martin et al., 2001). The water supplies for such systems can be provided naturally in parts of British Columbia and eastern Canada. In other parts of the country, water inputs for this purpose may be much harder to sustain.

Design of waste-disposal facilities to withstand specific flooding events is hampered in most mining districts by a lack of long-term hydrological data from which predictive calculations can be made. However, this is not the only factor. At the Mattachewan tailings site in Ontario, breach of a beaver dam increased water flows to the magnitude expected during a 200-year event at a facility designed for the nominal 100-year event. As a result, a dam cracked due to flooding of the dam foundation and tailings were discharged to the Montreal River resulting in large-scale downstream contamination. Natural floods of a similar magnitude could lead to similar consequences. According to Davies (2002), there has been a major tailings dam failure every year somewhere in the world over the past few decades. These failures are attributed primarily to damage to dam foundations and to overtopping, causing dam instability and in some cases liquefaction of the tailings (e.g., Hudson-Edwards et al., 2003; see also data from International Commission on Large Dams and U.S. Commission of Large Dams summarized in Strachan, 2002). Examples since 1994 include the tailings dam failures at Merriespriut, South Africa (1994); Omai, Guyana (1995); Pinto Valley, U.S. (1997); Los Frailes, Spain (1998); and Aurul, Romania (2000). In addition to these major failures, numerous examples of less catastrophic physical failures have been documented. Increased rainfall can also cause chemical failures where increased volumes of contaminated water discharge through the dams and are released downstream (Macklin et al., 2003).

Accurate prediction of runoff within the containment area is critical in the design of collection and treatment systems for contaminated drainage. If excess flow occurs, it will not all be collected and treatment systems may not be able to operate at the capacity required to prevent downstream contamination. These occurrences can have negative impacts on downstream ecosystems and maintenance of freshwater supplies for other users. For example, at the Equity mine in British Columbia, the collection system was designed to handle a 100-year flood. Inaccurate prediction has led to unplanned discharge during lesser flood events in two of the last five years. In this case, the design of the collection system used inaccurate runoff forecasting. The 2000 tailings dam failure at Aurul (Baie Mare), Romania, provides a catastrophic example: rain on late snow led to flooding in excess of the design threshold. More accurate hydrological data and methods for projecting future hydrologic conditions would improve the design of containment facilities.

Wetting and drying cycles are a normal climatic variation. During dry periods, soluble efflorescent salts can accumulate in mine wastes. The first precipitation events after periods of low or no precipitation can result in increased concentrations of metals and acid in receiving waters (Alpers et al., 1994; Jambor et al., 2000). If wet and dry cycles increase in Canada, for example due to climatic changes, there may be larger fluctuations in concentrations as is currently observed in arid and semi-arid regions of the U.S. In addition to sulphide mine wastes, this issue may affect the large-scale high-grade uranium deposits in northern Saskatchewan and the territories, where uranium minerals are subject to oxidation.

The initiation of diamond mining in Canada introduces some new issues regarding water use. Despite the presence of apparently extensive surface water in the north, much of the terrain is actually semi-arid by most climatic classifications. As a result, there may be limited water available for dilution of mine effluent.

These new mines have also resulted in increased interest in the use of permafrost both for dams and as a means of limiting sulphide oxidation. Greater information on the long-term impact of permafrost development on water consumption and water quality management is required.

The volume of aggregate removed from pits and quarries is large. At any given time, there are many thousands of aggregate operations in Canada. Small aggregate operations are numerous and often follow construction activities. Near urban centres, aggregate operations are usually larger and can last for several decades or longer. Where water tables are high, extensive dewatering is required to gain access to rock and gravel. This dewatering can affect local water supplies and water levels of adjoining surface water bodies. Washing activities can result in increased suspended solids. Impacts do not usually persist long after aggregate removal is complete. In urban areas, as shallow aggregate sources diminish, deeper operations become viable, and dewatering activities intensify. There are numerous examples in urban areas of Canada, such as Calgary and Toronto, where intake for aggregate production conflicts with other demands such as municipal, industrial and recreational uses. With increased urbanization, these conflicts are expected to increase in frequency.

Oil and Gas Extraction Sector

The volume of water required for petroleum production is growing as formation flooding increases and as large oilsand operations are initiated. In western Canada, large volumes of surface and ground water are used for formation injection. Each year thousands of new groundwater supply wells are drilled and surface water continues to be diverted as source water for petroleum extraction. Shallow groundwater is inexpensive to pump; generally fresh, it is a sought-after resource for other purposes, including domestic and agricultural purposes. As pressure for other needs increases, efforts have been made in the arid and semi-arid west to more efficiently use available water.

While the overall volume of water consumed for petroleum production has been increasing, the volume of water diverted from fresh surface and ground water sources has been declining. In Alberta, 88.7 million cubic metres of diverted water was used in 1973, compared to 47.5 million cubic metres in 2002, representing a reduction of 46% (Alberta Environment, 2003). Other sources of make-up water are increasingly being used, including recycled water and brackish and saline water. Although the volume of diverted water is declining, the volume currently used is still substantial. In Alberta in 2002, 26.9 million cubic metres of surface water and 10.1 million cubic metres of non-saline groundwater were used for formation injection. With time, as oil fields age, the produced volume of water increases and less water is required for make-up water. In areas of new activity, large volumes of water will continue to be required. Water will also still be required for tertiary extraction methods as economic conditions warrant enhanced recovery. Water use for injection purposes is carefully monitored and, for Alberta, has been recently compiled in a detailed report (Alberta Environment, 2003).

Large quantities of surface and ground water are also consumed in the production of heavy crude from oilsand deposits. There is a desire to initiate greater production of oil from oilsands, but because of competing water demands for agricultural and increased urbanization in regions with oilsands, further production of oilsands at this time is becoming more controversial. There are currently more than a dozen oilsand projects that are operating or planned in Alberta. There are large organized initiatives in Alberta and Saskatchewan that have been established to balance water needs for the production of petroleum products and other users.

Coalbed methane extraction is gaining increasing attention. Coal deposits are dewatered to enhance methane recovery. It is likely that these operations will increase in scale and number. The water demands for these operations require quantification. Coalbed methane extraction operations can range from relatively small local operations to large-scale operations. New methods for petroleum recovery will each require an assessment of water demand in context of other uses in a region.

Knowledge and Program Needs

The primary threat posed by the mineral extraction industry to freshwater availability in Canada is not the direct intake of water during active ore extraction, but rather the release of water of substandard quality long after ore extraction is complete. For the petroleum extraction industry, the primary threat to freshwater availability in Canada is the diversion of surface and ground water for injection purposes and the utilization of water for oilsand operations. The degradation of water quality from current and legacy petroleum operations also requires consideration. Recommendations for knowledge and program needs include the following.

- Improve databases on the drainage chemistry and contaminant loadings, along with the number, size and location of all mine workings and waste deposits, active and inactive, in Canada.
- Improve ability to predict future drainage chemistry from mine wastes and workings at active and inactive mines.
- Improve understanding of potential mitigation requirements, including required maintenance and repair at inactive mine sites.

- Assess the magnitude of surface and ground water contamination by mine sites in different regions and hydrological settings in Canada.
- Improve long-term forecasting of climate extremes: probable maximum flood, climate variability, and role of long-term climate change on climate extremes.
- Expand baseline climate monitoring network, including basic hydrographic monitoring of rivers that allow integrated understanding of basin-wide effects of climate, rainfall and anthropogenic changes, and precipitation/temperature/snowpack conditions (e.g., depth and water content) at locations where mining occurs.
- Improve estimates of water supplies for semi-arid and arid regions (ground and surface water availability, groundwater mining), particularly in petroleum-producing regions (e.g., Alberta and Saskatchewan) but also regions with fertilizer, diamond and metal production. Regional demographic projections also need to be included.
- Use improved forecasting of climate variability and water quality issues to improve waste handling and mitigation, including the special subtopic of permafrost.
- Capacity building within all sectors of the mining industry and improved collaboration between researchers and practitioners – e.g., industry/community/government/academic partnerships to evaluate detailed, long-term water and mass-balances at mine sites – including long-term relationships at specific mines in characteristic regions.
- Address combined technical/sociological water issues for First Nations, and in special ecological zones and protected parks.
- Assess and improve management of water in uranium mining districts.

References

Alberta Environment. 2003. Water use for injection purposes in Alberta. ISBN No. 0-7785-3000-0.

Alpers, C.N., D.K. Nordstrom and J.M. Thompson. 1994. Seasonal variations of Zn/Cu ratios in acid mine water from Iron Mountain, California, p. 324-344. *In* Alpers, C.N. and D.W. Blowes (ed.), Environmental geochemistry of sulphide oxidation. American Chemical Society Symposium Series 550.

Baker, M.J., D.W. Blowes, M.J. Logsdon and J.L. Jambor. 2003. Environmental geochemistry of kimberlite materials: Diavik Diamonds Project, Lac De Gras, Northwest Territories, Canada. Exploration Mining Geology 10: 155-163.

Blowes, D.W. and J.L. Jambor. 1990. The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Québec, Canada. Appl. Geochem. 5: 327-346.

Blowes, D.W., C.J. Ptacek and J.L. Jambor. 1994. Remediation and prevention of low-quality drainage from mine wastes, p. 365-380. *In* Jambor, J.L. and D.W. Blowes (ed.), Short course handbook on environmental geochemistry of sulphide mine-wastes. Mineralogical Association of Canada, 22.

Blowes, D.W., E.J. Reardon, J.L. Jambor and J.A. Cherry. 1991. The formation and potential importance of cemented layers in inactive sulphide mine tailings. Geochimica et Cosmochimica Acta 55: 965-978.

Coggans, C.J., D.W. Blowes, W.D. Robertson and J.L. Jambor. 1998. The hydrogeochemistry of a nickel-mine tailings impoundment, Copper Cliff, Ontario. Reviews in Economic Geology 6B: 447-465.

Davies, M.P. 2002. Tailings impoundment failures: are geotechnical engineers listening? Geotechnical News, September, 2002: 31-36.

Davis, A. and G.D. Ashenberg. 1989. The aqueous geochemistry of the Berkeley Pit, Butte, Montana, U.S.A. Appl. Geochem. 4: 23-36.

Eary, L.E. 1999. Geochemical and equilibrium trends in mine pit lakes. Appl. Geochem. 14: 963-987.

Environment Canada. 2002. Industrial water use, 1996. Minister of Public Works and Government Services Canada, Ottawa, Ontario.

Feasby, D.G., M. Blanchette and G. Tremblay. 1991. The mine environment neutral drainage program, p. 1-26. *In* Second international conference on the abatement of acidic drainage, Montreal, Quebec, Sept. 16-18, 1991.

Feasby, G. and G. Tremblay. 1995. New technologies to reduce environmental liability from acid generating mine wastes, vol. 2, p. 643-647. *In* Proceedings Sudbury '95 mining and the environment.

Government of Canada. 1991. State of Canada's Environment. Ministry of Supply and Services, Ottawa.

Hudson-Edwards, K.A., M.G. Macklin, H.E. Jamieson, P.A. Brewer, T.J. Coulthard, A.J. Howard and J.N. Turner. 2003. The impact of tailings dam spills and clean-up operations on sediment and water quality in river systems: the Ríos Agrio-Guadiamar, Aznalcóllar, Spain. Appl. Geochem. 18: 221-239.

ICOLD. 1996. A guide to tailings dams and impoundments: design, construction, use and rehabilitation. International Commission on Large Dams, Bulletin. United Nations Environment Programme. No. 106. 239 p.

Jambor, J.L., D.K. Nordstrom and C.N. Alpers. 2000. Metal-sulfate salts from sulphide mineral oxidation. Reviews in Mineralogy and Geochemistry 40: 303-350.

Johnson, R.H., D.W. Blowes, W.D. Robertson and J.L. Jambor. 2000. The hydrogeochemistry of the Nickel Rim mine tailings impoundment, Sudbury, Ontario. J. Contam. Hydrol. 41: 49-80.

Kleinmann, R.P.L. 1990. Acid mine drainage: an overview, p. 281-282. *In* Hobbs, B.F. (ed.), Proceedings of conference energy in the 90s. American Society of Civil Engineering, New York.

Levy, D.B., K.H. Custis, W.H. Casey and P.A. Rock. 1997. The aqueous geochemistry of the abandoned Spenceville

Copper Pit, Nevada County, California. J. Environ. Qual. 26: 233-243.

Macklin, M.G., P.A. Brewer, D. Balteanu, T.J. Coulthard, B. Driga, A.J. Howard and S. Zaharia. 2003. The long term fate and environmental significance of contaminant metals released by the January and March 2000 mining tailings dam failures in Maramures County, upper Tisa Basin, Romania. Appl. Geochem. 18: 241-257.

Martin, A.J., J.J. McNee and T.F. Pedersen. 2001. The reactivity of sediments impacted by metal-mining in Lago Junin, Peru. J. Geochem. Explor. 74: 175-187.

Miller, G.C., W.B. Lyons and A. Davis. 1996. Understanding the water quality of pit lakes. Environ. Sci. Technol. 30: 118-123A.

Moncur, M.C., C.J. Ptacek, D.W. Blowes and J.L. Jambor. 2003. Fate and transport of metals from an abandoned tailings impoundment after 70 years of sulfide oxidation, p. 238-247. *In* Proceedings of Sudbury '03, mining and the environment III, May 2003, Sudbury, Ontario.

Morin, K.A. and N.M. Hutt. 1997. Environmental geochemistry of minesite drainage: practical theory and case studies. MDAG Publishing, Vancouver, B.C.

Nordstrom, D.K. and C.N. Alpers. 1999. Negative pH, efflorescent mineralogy, and consequences for environmental restoration at the Iron Mountain Superfund site, California, p. 3455-3462. *In* Proceeding of the National Academy of Science, U.S.A., 96.

Nordstrom, D.K., C.N. Alpers, C.J. Ptacek and D.W. Blowes. 2000. Negative pH and extremely acidic mine waters from Iron Mountain, California. Environ. Sci. Technol. 34: 254-258.

Price, W.A. 1999. Regulation as a tool for reducing the risks associated with metal leaching and acid rock drainage. Mine Reclamation Section, British Columbia Ministry of Energy and Mines. 29 p.

Price, W.A. 2001. Use of fresh water covers as a mitigation strategy at mine sites in British Columbia. *In* Price, W.A. (ed.), New developments, different aspects of prediction and the use of water covers as a mitigation strategy. Presentations at the 8th Annual BC MEM - MEND Metal Leaching and ARD Workshop, Vancouver, British Columbia, November 28-29, 2001.

Price, W.A. and K. Bellefontaine. 2002. Mitigation of metal leaching and acid rock drainage in environmental trends in British Columbia: 2002. British Columbia Ministry of Water, Land and Air Protection.

Price, W.A. and J. Errington. 1998. Guidelines for metal leaching and acid rock drainage at minesites in British Columbia. British Columbia Ministry of Energy and Mines. 86 p.

Price, W.A. and B. Hart (ed.). 1999. Proceedings of workshop on molybdenum issues in reclamation. British Columbia Committee on Molybdenum Issues in Reclamation. British Columbia Ministry of Energy and Mines.

Ramstedt, M., E. Carlsson and L. Lövgren. 2003. Aqueous geochemistry in the Udden pit lake, northern Sweden. Appl. Geochem. 18: 97-108.

Roderick, M.L. and G.D. Farquhar. 2002. The cause of decreased pan evaporation over the past 50 years. Science 298: 1410-1411.

Shevenell, L., K.A. Connors and C.D. Henry. 1999. Controls on pit lake water quality at sixteen open-pit mines in Nevada. Appl. Geochem. 14: 669-687.

Strachan, C. 2002. Review of tailings dam incident data. Mining Environment Management, January 2002: 7-9.

USDA. 1993. Acid drainage from mines on the National Forest: a management challenge. U.S. Forest Service Publication 1505, p. 1-12.

Vigneault, B., P.G.C. Campbell, A. Tessier and R. de Vitre. 2001. Geochemical changes in sulfidic mine tailings stored under a shallow water cover. Water Res. 35: 1066-1076.

Wireman, M. 2002. Potential water-quality impact of hard-rock mining. Ground Water Monit. Remediat., Summer: 40-51.

Yanful, E.K. and A. Verma. 1999. Oxidation of flooded mine tailings due to resuspension. Can. Geotech. J. 36: 826-845.

Chapter 10

CLIMATE VARIABILITY AND CHANGE – GROUNDWATER RESOURCES

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Current Status

It has long been known that natural climate variability and climate change both affect water levels in aquifers. One can predict that as an important part of the hydrologic cycle, groundwater resources will be affected by climate change in relation to the nature of recharge, the kinds of interactions between the groundwater and surface water systems, and changes in water use (e.g., irrigation). We expect that changes in temperature and precipitation will alter recharge to groundwater aquifers, causing shifts in water table levels in unconfined aquifers as a first response (Changnon et al., 1988; Zektser and Loaiciga, 1993). Decreases in groundwater recharge will not only affect water supply, but may also lead to reduced water quality. There may also be detrimental environmental effects on fisheries and other wildlife as a result of changes to the baseflow dynamics in streams (e.g., Gleick, 1986). Other potential impacts include altering the equilibrium in coastal aquifers (e.g., Custodio, 1987; Lambrakis, 1997; Vengosh and Rosenthal, 1994), and reducing the volume of water stored in aquifers with associated potential for increased land subsidence (e.g., California, Mexico City).

From a regional or national perspective, our understanding of climate variability and change impacts on groundwater resources – related to availability, vulnerability and sustainability of freshwater – remains limited. Two important factors serve to complicate and limit our understanding and ability to measure these potential impacts directly.

Timing of Recharge: Climate variability is defined as the natural, often cyclic, and high frequency variation in climate. In contrast, climate change may be either natural or human-induced, and displays longer-term trends. While surface waters typically see rapid response to climate variability, the response of groundwater systems is often difficult to detect because the magnitude of the response is lower and delayed. Longer-term variations in climate are often well preserved in aquifers (e.g., Pleistocene climate impacts). Thus, the magnitude and timing of the impact of climate variability and change on aquifers, as reflected in water levels, are difficult to recognize and quantify. This is because of the difference in time frame that exists between climate variations and the aquifer's response to them.

Aquifer Character: Different types of aquifers respond differently to surface stresses. Shallow aquifers consisting of weathered or fractured bedrock or unconsolidated sediments are more responsive to stresses imposed at the ground surface compared to deeper aquifers. These tend to be more isolated from surface conditions by overlying aquitards (e.g., van der Kamp and Maathuis, 1991a). Similarly, shallow aquifers are affected by local climate changes, whereas water levels in deeper aquifers are affected by regional changes. Therefore, climate variability, being of relatively short term compared to climate change, will have greater impact on these shallow aquifer systems. In contrast, deep aquifers have an increased capacity to buffer the effects of climate variability, and are therefore able to preserve the longer-term trends associated with climate change. It is important to note, however, that deep aquifers can be vulnerable to climate variability. As shallow groundwater resources become limited or contaminated, deeper groundwater resources are often exploited (e.g., Texas).

Trends

Groundwater Level Data

Groundwater level data provide a direct means of measuring the impacts of both natural and anthropogenic changes to groundwater resources. The stresses caused by these changes affect recharge to, storage in, and discharge from aquifers (e.g., Taylor and Alley, 2001; Gilliland, 1967), and generally alter or disrupt the overall water balance. Most hydrogeologic assessments, which are conducted for the purpose of aquifer characterization, modelling, and yield assessment, include some analysis and interpretation of well hydrograph data.

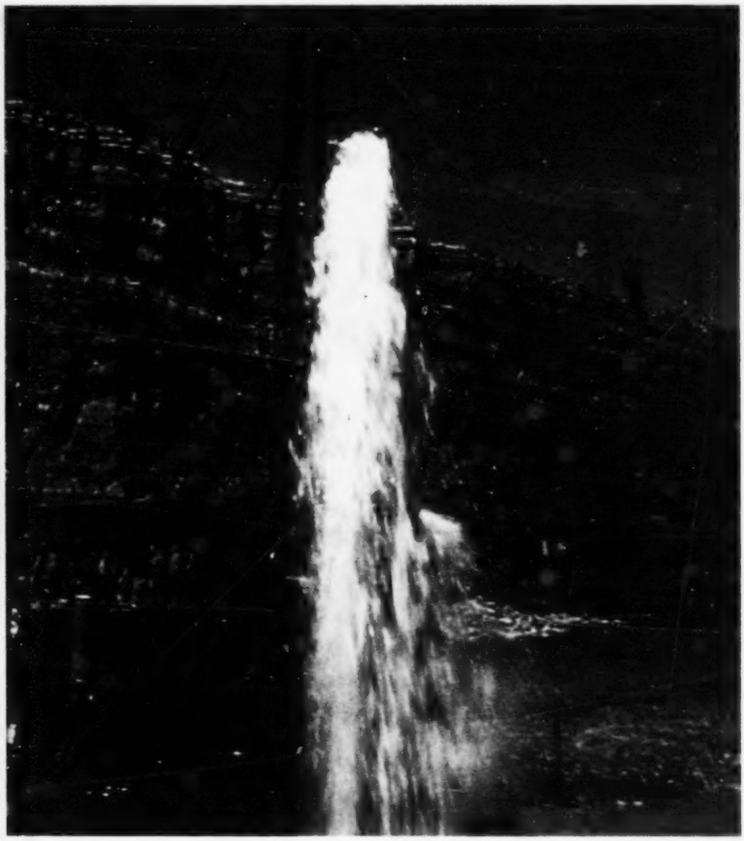
Despite the fact that some groundwater level networks have been in operation for decades, there are only a few publications providing an interpretation of hydrographs. Gabert (1986) and Maathuis and van der Kamp

(1986) provided a qualitative assessment of hydrographs for Alberta and Saskatchewan, respectively. In addition, van der Kamp and Maathuis (1991a) and van der Kamp and Schmidt (1997) showed that hydrographs for deep semi-confined aquifers can be used for assessment of soil moisture conditions at a regional scale. To date, little has been done in Canada to relate hydrographs to climatic variables (e.g., Rutulis, 1989; Chen and Grasby, 2001; Rivard et al., 2003), nor have hydrograph data been used systematically to specifically address the question of the impact of climate variability on aquifers and groundwater resources.

Potential Impacts

Some of the most important potential impacts to groundwater are described further below.

Recharge: Spatial and temporal changes in temperature and precipitation may act to modify the surface hydraulic boundary conditions of, and ultimately cause a shift in the water balance for, an aquifer. For example, variations in the amount of precipitation, the timing of precipitation events, and the form of precipitation are all key factors in determining the amount and timing of recharge to aquifers. Water levels in an aquifer are often observed to respond consistently to precipitation, although the nature of the response can be complex and depends on time of year and prior conditions, etc. These data may be used in calibrating numerical models because they provide a temporal record of the aquifer response to recharge. In most instances, the water level response to precipitation is positive, slightly delayed in the aquifer, attenuated with depth, and is more pronounced in unconfined than in semi-confined aquifers. However, recent studies have shown that increased annual precipitation does not necessarily correspond to an increase in recharge as would be anticipated (e.g., Rivard et al., 2003; Nastev et al., 2002).



Groundwater is a precious resource and might be affected by land use and climate change.

The occurrence of droughts or heavy precipitation can also be expected to impact water levels in aquifers. Droughts result in declining water levels not only because of reduction in rainfall, but also due to increased evaporation and a reduction in infiltration that may accompany the development of dry topsoils. Extreme precipitation events (e.g., heavy rainfall and storms) may lead to less recharge to groundwater because much of the precipitation is lost as runoff. However, in Manitoba, infrequent heavy rainfall events, in the order of a 1-in-10 or 1-in-50 year storm, can "top up" aquifers that have suffered from years of decline (Betcher, pers. comm.). So, despite the fact that over the course of a year cumulative precipitation may be greater for an area, the total amount of recharge to the aquifer may be less.

Variations in temperature and precipitation, along with other factors, such as wind speed, vegetation, etc., will affect evapotranspiration. Determining evapotranspiration is difficult even when site-specific data are available. Predicting changes to rates and magnitudes of evapotranspiration that might accompany climate change, and thus impact groundwater resources in an aquifer will be particularly challenging. To date, there are few studies that address this issue.

Groundwater-Surface Water Interactions: In many regions of Canada, groundwater interacts strongly with surface water. Thus, the interactions between surface and ground water are important mechanisms to consider since they play a vital role in supporting ecosystems. The intimate relationships between ground and surface water imply that these resources must be treated as an integrated resource rather than as separate ones.

Interactions between surface and ground water include, but are not limited to:

- wetlands, which are supported and interact strongly with groundwater in some areas
- streamflow, which is sustained by groundwater when contributions from direct precipitation are lacking (baseflow) (Arnell, 1996)
- influent rivers, which contribute recharge to aquifers

- springs, which are groundwater discharge features, and
- coastal waters, which receive discharging fresh groundwater to support delicate ecosystems.

Therefore, climate variability as it affects any one of these environments will not only impact groundwater resources, but impacts to aquifers will affect each of these as well. For example, shifts in the nature of the stream discharge curves have the potential to influence significantly water levels in aquifers. Under various climate change scenarios for British Columbia, higher peak discharge and an earlier onset and more prolonged baseflow period are predicted for many rivers (Leith and Whitfield, 1998). For those aquifers that are in good hydraulic connection to rivers, rising water tables might accompany spring flood events and longer periods of declining water tables will occur through the late summer and early fall. Reductions to glacier runoff over the next several decades will also see a major impact on many river and aquifer systems as these rely on glacier melt during the late summer months to sustain baseflow and water levels in aquifers (Brugman et al., 1997).

Flow Regimes

Climate variability and change may be important considerations for overall changes to the flow regime. Coastal aquifers are used here as an example, but other complex aquifer systems (that might have fluids of different densities or levels of contamination, or natural quality variations) may be similarly affected. Coastal aquifers are sensitive to changes in water budget due to the interaction between fresh and salt water in the subsurface along the coast. When recharge is lowered, the position of the freshwater-saltwater interface will move inland at a rate that is proportional to the reduction in recharge, and water quality can be compromised to the extent that freshwater availability is limited. Similarly, changes in sea level that might accompany climate change affect the position of this interface. A complicating factor is land-use development, which has increased in most coastal regions of Canada (e.g., Nova Scotia, Prince Edward Island, lower mainland of British Columbia). Upconing or encroachment of the freshwater-saltwater interface due to increased pumping of groundwater is a potential threat.

Groundwater Storage

As the various inputs to (recharge) and outputs from (discharge) aquifers are affected, so too will be the overall storage of groundwater in an aquifer. Over the long term, and in the absence of any major changes to annual budgets that might, for example, be caused by groundwater pumping, the water budget for an aquifer is generally in dynamic equilibrium. This means that cyclic climate variability does occur and does affect water levels, but over the long term, the system is in dynamic equilibrium. Short-term (or moderate-term) variability is reflected in the hydrographs as cyclic variation. Long-period trends in hydrographs that are superimposed over the high-frequency variations reflect changes in groundwater storage that might be the result of groundwater overexploitation (excessive pumping) or climate change. When groundwater is removed from storage, water levels in the aquifer drop, and when water is added to storage, the water levels rise. In aquifers that contain layers or lenses of geologic materials that are easily compacted (e.g., clay), reductions in storage may potentially increase the effective stress on geologic units leading to compaction and land subsidence.

Increased Demand

Increased irrigation is perhaps the most obvious reason why there may be an increased demand for groundwater as an alternative or supplemental supply of water. From a global perspective, climate change impacts to other nations may limit their ability to grow food. An increase in Canadian food export will result in greater consumption of freshwater in Canada, some of which will most certainly be groundwater.

Changes in the demand for groundwater are also likely to occur as development increases and as land use changes or intensifies. While these effects will largely be driven by population increase, climate variability and change may play some role. For example, if shallow aquifers experience significant impacts, it may be necessary for some regions to seek additional groundwater resources from deeper aquifers. Therefore, while the overall demand may be lowered for some aquifers, it may increase for others.

Potential lower recharge to aquifers may prove to be limiting factors to water availability in many regions. This may occur particularly when evapotranspiration losses might be greater under climate change conditions, and when water use might rise to accommodate growing populations, increased use for agriculture and irrigation, etc.

Impact Studies

In Canada, most research on the potential impacts of climate change to the hydrologic cycle has been directed at forecasting the potential impacts to surface water, specifically the links between glacier runoff and river discharge (e.g., Whitfield and Taylor, 1998; Leith and Whitfield, 1998). Relatively little research has been undertaken to determine the sensitivity of aquifers to changes in the key climate change variables, precipitation and temperature. Internationally, only a few studies have been reported in the literature on the impacts of climate change (based on predictive scenarios) to groundwater resources (e.g., Vaccaro 1992; Rosenberg et al., 1999; McLaren and Sudicky, 1993). Aquifer recharge and groundwater levels interact and depend on climate and groundwater use; each aquifer has different proper-

Three Groundwater Studies in Canada that Consider Climate Variability and Change

The Great Lakes Basin

The impacts of climate change on groundwater conditions within the Great Lakes basin have been estimated using the Grand River watershed and western southern Ontario as prototypes. Methods of analysis have varied from regional-scale groundwater modelling to the analysis of stream flow to determine groundwater levels and discharge (or base flow) as a function of historic and future climatic conditions.

The Government of Canada's Climate Change Action Fund supported the studies that were conducted across western southern Ontario. They were conducted by the National Water Research Institute and Meteorological Service of Canada in collaboration with the Geological Survey of Canada and Ontario ministries of the Environment and Natural Resources (e.g., Piggott et al., 2001). Streamflow data for a network of 174 watersheds were separated into surface runoff and groundwater discharge components and analyzed in a time series context. The results of this analysis indicate that as much as 75 percent of melting snow and rain is available for runoff and groundwater recharge during the winter, while as little as 10 percent is available during the summer. The portion of this excess precipitation that recharges groundwater is a function of physiography and varies from 10 to 80 percent when calculated by watershed. The rate at which the recharge subsequently discharges to form base flow, and therefore the persistence of this flow, is also a function of physiography.

These results were used in combination with two climate change scenarios to determine the potential impacts on groundwater conditions. Averaged over the watersheds, the two scenarios resulted in a 19% increase and a 3% decrease, respectively, in total annual base flow. The two scenarios also resulted in a significant, and more consistent, impact on the annual distribution of base flow. The study predicted increased flows during the winter due to a reduction in snow accumulation and decreased flows during the spring and early summer due to the corresponding decrease in snow melting. These results clearly indicate a potential for significant impacts on groundwater conditions and therefore water supplies, instream conditions, and aquatic habitat. These impacts are due to only the interaction of climate and groundwater; impacts due to changing water use are also probable.

Carbonate Aquifer in Winnipeg

Research on the regional carbonate aquifer in Winnipeg showed that freshwater hydraulic heads, measured southwest of Winnipeg, help keep a saline groundwater on the west side of the Red River from migrating eastward. It also showed that the saline/freshwater boundary is strongly controlled by river systems (Charron, 1965; Grasby and Betcher, 2002). Charron (1965) showed that the boundary was west of the Red River and south of the Assiniboine River in the early 1900s. He also suggested that heavy pumping in the freshwater zone in the early 1900s caused saline water to move across the rivers into freshwater zones in the Winnipeg area. Eastward movement of the boundary was also observed in response to dewatering during construction of the Winnipeg floodway (Render, 1970). Decreases in pumping in the last 30 years have resulted in the boundary moving back to its previous position. Chen and Grasby (2001) analyzed water-well levels in Winnipeg, built an analytical model, and performed simulations to evaluate the effects that long-term climate changes would have on water levels in the freshwater bearing portions of the aquifer.

An empirical relationship between key climate variables was used to relate precipitation and temperature with groundwater recharge, and thus, hydraulic head in the aquifer, based on historic monitoring well network data (Chen et al., 2002). The empirical model could predict heads based on precipitation and temperature. Using future climate change scenarios, projected temperature and precipitation trends were used to calculate hydraulic heads at various points in the aquifer for the year 2030.

Under some climate scenarios the freshwater zone showed net change in hydraulic head from the year 2000. Predicted drops in head near the Red River, southeast of Winnipeg, suggest that the saline/freshwater boundary could potentially move eastward in response to climate change, causing salinization of water wells.

Grand Forks Aquifer, British Columbia

Allen et al. (In press) attempted an integrated climate change sensitivity analysis for the Grand Forks aquifer in south-central British Columbia. They considered both climate variables and changes to surface hydrology. Projected ranges of precipitation and temperature, based on Global Climate Model results for the South British Columbia Mountains Climate Region, were used to estimate minimum and maximum values for recharge. Recharge values were subsequently input into a numerical hydrogeologic model of the aquifer. The sensitivity of water levels in the aquifer to changes in river stage was also investigated. Because the Grand Forks aquifer exhibits strong interaction between ground and surface waters of the Kettle and Granby rivers, variations in river stage water levels were shown to be much more sensitive to river stage variation than to recharge variation. Ongoing work is addressing the temporal/seasonal behaviour of the system in an effort to examine changes in storage that may prove important for assessing demand issues in the dry summer months.

ties and requires detailed characterization and eventually quantification (e.g., numerical modelling) of these processes and linking the recharge model to climate model predictions (York et al., 2002).

Knowledge and Program Needs

With the purpose of increasing our knowledge on groundwater availability as a first step to assessing impacts from climate changes, several key areas require additional understanding and study in Canada.

Resource Inventory

Even without climate change, increased demand for water can be expected because of population growth, ongoing industrialization and agricultural demands. In addition, there is an increased need for protection of both surface and ground water resources by means of establishing land-use guidelines. Consequently, there will be an increasing need for aquifer resource inventories and aquifer characterizations, particularly in populated areas.

Knowledge Gaps

- The impacts of climate variability and change will vary across Canada, not only due to differences in climate from region to region, but also due to the nature of the groundwater system being affected. Regional case studies involving detailed characterization of aquifers are required to gain a better understanding of the potential impacts on groundwater resources.
- The impacts of climate variability and change on groundwater recharge are not well understood and are a major deficiency in current groundwater models.
- The dynamics of the interaction between shallow aquifers and surface water are poorly understood and not well studied in Canada.

To address these knowledge gaps, historic and future climatic and hydrologic data will be of critical importance for describing changes to the overall water balance and flow regime within an aquifer system, and managing the resource into the future.

Monitoring

Groundwater level measurements from observation wells are the principal source of information on the effects of hydrologic stresses on groundwater systems. These data in combination with precipitation records, streamflow and withdrawal data are essential for monitoring the effectiveness of groundwater management and protection schemes. Similar to streamflow and climatic data, groundwater level data become progressively more valuable with increased record length and continuity. Groundwater level data from observation well networks are available for all provinces (Maathuis, In progress). However, in contrast to streamflow and climatic data, which may have records up to 100 years in length, groundwater level records are typically less than 25 years in length and seldom longer than 40 years. Furthermore, relatively few wells are strategically situated near climate and/or streamflow stations making analysis and comparison difficult. Also, in the past decade networks have suffered from budget cuts, resulting in a reduction in the number of groundwater level observation wells and interruption in the continuity of records.

Data on groundwater withdrawal are similarly critical in assessments of the behaviour of water levels in aquifers. Without withdrawal data, it is impossible to separate the impact of pumping from that caused by climatic variability and change. While in many parts of Canada groundwater withdrawal licences are required for non-domestic groundwater use, reliable withdrawal data are often absent.

The available data that could be used to support any evidence of impacts of climate variability and change on groundwater resources are insufficient and of very short duration. Therefore, the collection of the following long-term data is critical.

Water Level Data: A Canada-wide network of observation wells for long-term groundwater level monitoring should be established. The network should include wells completed in both stressed and natural environments. It also should be tied into the climate and streamflow networks.

Groundwater Withdrawal Data: Information about groundwater withdrawals (pumping) is critical to the proper interpretation of water-level data and a basic input parameter into groundwater models.

Modelling

Well-calibrated groundwater models could be used to simulate and anticipate the possible impacts of climate change on the sustainability of groundwater resources. Models should be built to simulate and predict:

- groundwater changes due to human actions (pumping)
- interactions with surface water bodies (rivers, streams, lakes and wetlands)
- climate variability (hydrological cycle scale), and
- climate change (long-term scale).

In addition to the above, models could be excellent tools for water management, when used for assessing the natural sustainable yield of aquifers and their vulnerability to contamination.

Institutional

The following institutional considerations are also recommended:

- encouraging watershed approaches to water management and protection
- increasing cooperation between federal and provincial agencies regarding implementation and operation of monitoring networks
- fostering linkages between water scientists and water managers
- promoting integrated water resource management
- promoting a network of compatible (i.e., standardized) groundwater databases, and
- promoting a groundwater resources inventory.

References

Allen, D.M., D.C. Mackie and M. Wei. Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. Hydrogeology Journal, In press.

Arnell, N. 1996. Global warming, river flows and water resources. John Wiley and Sons. Chichester, England.

Betcher, R.N. Personal communication.

Brugman, M.M., P.A. Raistrick and A. Pietroniro. 1997. Glacier related impacts of doubling atmospheric carbon dioxide concentrations on British Columbia and Yukon. *In* Taylor, E. and B. Taylor (ed.), Responding to global climate change in British Columbia and Yukon. Volume I of the Canada country study: climate impacts and adaptation. Environment Canada and B.C. Ministry of Environment, Lands and Parks.

Changnon, S.A., F.A. Huff and C.-F. Hsu. 1988. Relations between precipitation and shallow groundwater in Illinois. J. Climate 1: 1239-1250.

Charron, J.E. 1965. Groundwater resources of Winnipeg area, Manitoba. Geological Survey of Canada, Paper 64-23.

Chen, Z. and S. Grasby. 2001. Predicting variations in groundwater levels in response to climate change, upper carbonate rock aquifer, southern Manitoba. Natural Resources Canada, Geological Survey of Canada, Calgary.

Chen, Z., S.E. Grasby and K.G. Osadetz. 2002. Predicting average annual groundwater levels from climatic variables: an empirical model. J. Hydrol. 260: 102-117.

Custodio, E. 1987. Seawater intrusion in the Llobregat Delta, near Barcelona (Catalonia, Spain), p. 436-463. *In* Groundwater problems in coastal areas. Studies and reports in hydrogeology, no. 45. UNESCO, Paris.

Gabert, G.M. 1986. Alberta groundwater observation-well network. Alberta Research Council, Terrain Sciences Department, Earth Sciences Report, 86-1. 40 p.

Gilliland, J.A. 1967. Observation-well program. Department of Energy, Mines and Resources, Inland Waters Branch. 30 p.

Gleick, P.H. 1986. Methods for evaluating the regional hydrologic impacts of global climatic changes. J. Hydrol. 88: 97-116.

Grasby, S.E. and R.N. Betcher. 2002. Regional hydrogeochemistry of the carbonate rock aquifer, southern Manitoba. Can. J. Earth Sci. 39: 1053-1063.

Lambrakis, N. 1997. The impact of urbanisation of Malia coastal area (Crete) on groundwater quality. Environ. Geol. 36: 87-92.

Leith, R.M.M. and P.H. Whitfield. 1998. Evidence of climate change effects on the hydrology of streams in south-central British Columbia. Can. Water Resour. J. 23(3): 219-230.

Maathuis, H. Groundwater level observation well networks in Canada. Saskatchewan Research Council, In progress.

Maathuis, H. and G. van der Kamp. 1986. Groundwater observation well network in Saskatchewan, Canada, p. 565-581. *In* Proceedings of Canadian Hydrology Symposium No. 16, National Research Council Canada, NRCC No. 25514.

McLaren, R.G. and E.A. Sudicky. 1993. The impact of climate change in groundwater. Impacts of climatic change on water in the Grand River basin Ontario. University of Waterloo, Department of Geography Publications series, vol. 40.

Nastev, M., A. Rivera, R. Lefebvre and M.M. Savard. 2002. Hydrology and numerical simulation of the regional groundwater flow of the St. Lawrence Lowlands of Southwestern Quebec. Submitted for publication.

Piggott, A., D. Brown, B. Mills and S. Moin. 2001. Exploring the dynamics of groundwater and climate interaction, p. 401-408. *In* Proceedings of the 54th Canadian Geotechnical and 2nd Joint IAH-CNC and CGS Groundwater Specialty Conference. Canadian Geotechnical Society and the Canadian National Chapter of the International Association of Hydrogeologists.

Render, F.W. 1970. Geohydrology of the Metropolitan Winnipeg area as related to groundwater supply and construction. Can. Geotech. J. 7: 243-274.

Rivard, C., J. Marion, Y. Michaud, S. Benhammane, A. Morin, R. Lefebvre and A. Rivera. 2003. Étude de l'impact potentiel des changements climatiques sur les ressources en eau souterraine dans l'Est du Canada, Commission géologique du Canada, dossier public 1577. 39 p. et annexes.

Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan and J.G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. Climatic Change 42: 677-692.

Rutulis, M. 1989. Groundwater draught sensitivity of Southern Manitoba. Can. Water Resour. J. 14(1): 18-55.

Taylor, C.J. and W.M. Alley. 2001. Ground-water-level monitoring and the importance of long-term water-level data. U.S. Geological Survey, Circular 1217. 68 p.

Vaccaro, J.J. 1992. Sensitivity of groundwater recharge estimates to climate variability and change, Columbia Plateau, Washington. *In* Lettenmaier, D.P. and D. Rind (ed.), Hydrological aspects of global climate change. J. Geophys. Res. D Atmospheres 97(3): 2821-2833.

van der Kamp, G. and H. Maathuis. 1991a. Annual fluctuations of groundwater levels as a result of loading by surface moisture. J. Hydrol. 127(1-4): 137-152.

van der Kamp, G. and H. Maathuis. 1991b. Groundwater levels and climate change, p. 143-147. *In* Proceedings of NHRI Symposium No. 8, Using hydrometric data to detect and monitor climatic change, April 1991.

van der Kamp, G. and R. Schmidt. 1997. Monitoring of total soil moisture on a scale of hectares using groundwater piezometers. Geophys. Res. Lett. 24(6): 719-722.

Vengosh, A. and E. Rosenthal. 1994. Saline groundwater in Israel: its bearing on the water crisis in the country. J. Hydrol. 156: 389-430.

Whitfield, P.H. and E. Taylor. 1998. Apparent recent changes in hydrology and climate of coastal British Columbia, p. 22-29. *In* Mountains to sea: human interaction with the hydrologic cycle, Proc. Canadian Water Resources Association 51st Annual Conference, Victoria, B.C.

York, J.P., M. Person, W.J. Gutowski and T.C. Winter. 2002. Putting aquifers into atmospheric simulation models: an example from the Mill Creek Watershed, north-eastern Kansas. Adv. Water Resour. 25: 221-238.

Zektser, I.S. and H.J. Loaiciga. 1993. Groundwater fluxes in the global hydrologic cycle: past, present, and future. J. Hydrol. 144: 405-442.

Chapter 11

CLIMATE VARIABILITY AND CHANGE – RIVERS AND STREAMS

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Current Status

Canadians have a strong cultural link with water, a major facet of our heritage, our spirituality, and our economy. We are viewed globally, perhaps with envy, as having vast water resources in a pristine setting. While this is true in general, there are areas within Canada that are semi-arid and sensitive to even small departures from average precipitation. Other areas with visibly abundant resources, such as the Great Lakes basin, can suffer from local over-exploitation of the resource. Concern is growing that these precious water resources are further threatened by what is popularly referred to as climate change. Several recent studies (Adamowski and Bocci, 2001; Burn and Hag Elnur, 2002; Cunderlik and Burn, 2002; Pilon and Yue, 2002; Whitfield and Cannon, 2000; Yue et al., 2002a,b; Zhang et al., 2001) have investigated trends in the flow of rivers and streams occurring in natural basins across Canada. Different aspects of the hydrological regime have been analyzed, such as seasonal patterns, average flow conditions and their extremes.

These studies have found that different areas display markedly different trends and tendencies in streamflow, and there is no simple description possible for natural rivers and streams across Canada. Individual station results indicate that annual minimum and mean daily flows are increasing significantly in northern British Columbia, Yukon Territory and southern Ontario, with evidence of decreasing tendencies concentrated in southern British Columbia (see Fig. 1). Studies show that maximum flows are tending to decrease significantly across most of Canada, similar to those reported for the U.S. by Lins and Slack (1999). In essence, changes are occurring, but not in simple ways. At this time, it is not possible to attribute these results fully either to a changing climate, resulting from increased greenhouse gas concentrations, or to natural climate variability. These analyses have focussed on observations over the last several decades, and at times contradict hydrological simulations using Global Circulation Models (GCMs). The gap between retrospective analysis and model results is, from a hydrologic perspective, an area of concern.

All the above cited studies have used streamflow data from the Reference Hydrometric Basin Network (RHBN) (Harvey et al., 1999; Pilon and Kuylenstierna, 2000). This network has decreased in size from its original design and currently contains 200 plus stations representing basins with at least twenty years of record under stable or pristine conditions. Hydrometric stations within the RHBN, such as the subset shown in Fig. 1, are of particular importance for studies oriented to climate variability and change; however, analysis of the characteristics of stations indicates certain limitations. The network tends to be composed of large basins in the north and smaller basins in the south, with certain provinces having large gaps in spatial coverage. This underscores the importance of long-term continued funding to targeted hydrological data collection for monitoring ambient conditions, and the need to supplement the current network to allow smaller basins to be brought on-line in the North and to fill major geographic gaps. The current Canadian approach of a data collection process driven by immediate needs (e.g., hydropower production, flood control reservoir operation, apportionment) is unlikely to result in an adequate network for providing basic data to evaluate impacts of climate variability and change on water resources. Monetary commitment to such long-term data collection is needed.

Since the last hydrological atlas for Canada (1977), there has not been an update that reflects changes to historic patterns. Today, more dynamic techniques are needed to produce relevant estimates of current water availability. Canada should be in a position to know current water availability and changes that might be affecting regional and local availability for both regulated and natural basins.

Much effort has been expended in advancing knowledge of small-scale process hydrology (Buttle et al., 2000). Canadian researchers have also developed modelling capabilities for water resources management. These larger scale models, available to practitioners, such as WATFLOOD (Kouwen and Mousavi, 2002) and SLURP (Kite, 1995), have not built upon the understanding of physical processes established through small-scale hydrological studies. An added complexity to modelling streamflow conditions is accounting for human activities (e.g., land-use changes, consumptive use practices, diversions) as these can affect local water availability. Such modelling efforts require knowledge of local intervention (e.g., withdrawals for irrigation, changes in land use, etc.). Understanding climate change and variability in the broad Canadian context requires an enhanced understanding and a modelling capability that builds upon hydrological process knowledge and correctly represents human interventions. The separation of impacts of interventions from those of climate change and variability is the basis for estimation and prediction of water availability under Canada's diverse and changing circumstances.

The process of modelling water availability requires adequate hydrological data. In Canada, the density of existing networks is low, and sparsely populated areas have even fewer stations. Currently, our analysis and modelling capabilities suffer from a bias against observing streamflow in small watersheds and a lack of linkages among hydrological observing networks (e.g., streamflow, precipitation, humidity, evaporation). The lack of accurate and high-resolution input data limits our ability to model the response of catchments. In essence, detailed knowledge about the spatial and temporal distribution of precipitation is lacking, mainly due to the very low density of our climate network in several regions of Canada and to our inability to translate remotely sensed information into meaningful hydrological fields. This is also valid for a number of other essential parameters (e.g., permafrost conditions, soil moisture, radiation).

On the banks of the Yukon River. Studies show that annual flows are increasing in northern British Columbia, Yukon Territory and southern Ontario, while decreasing in southern British Columbia.

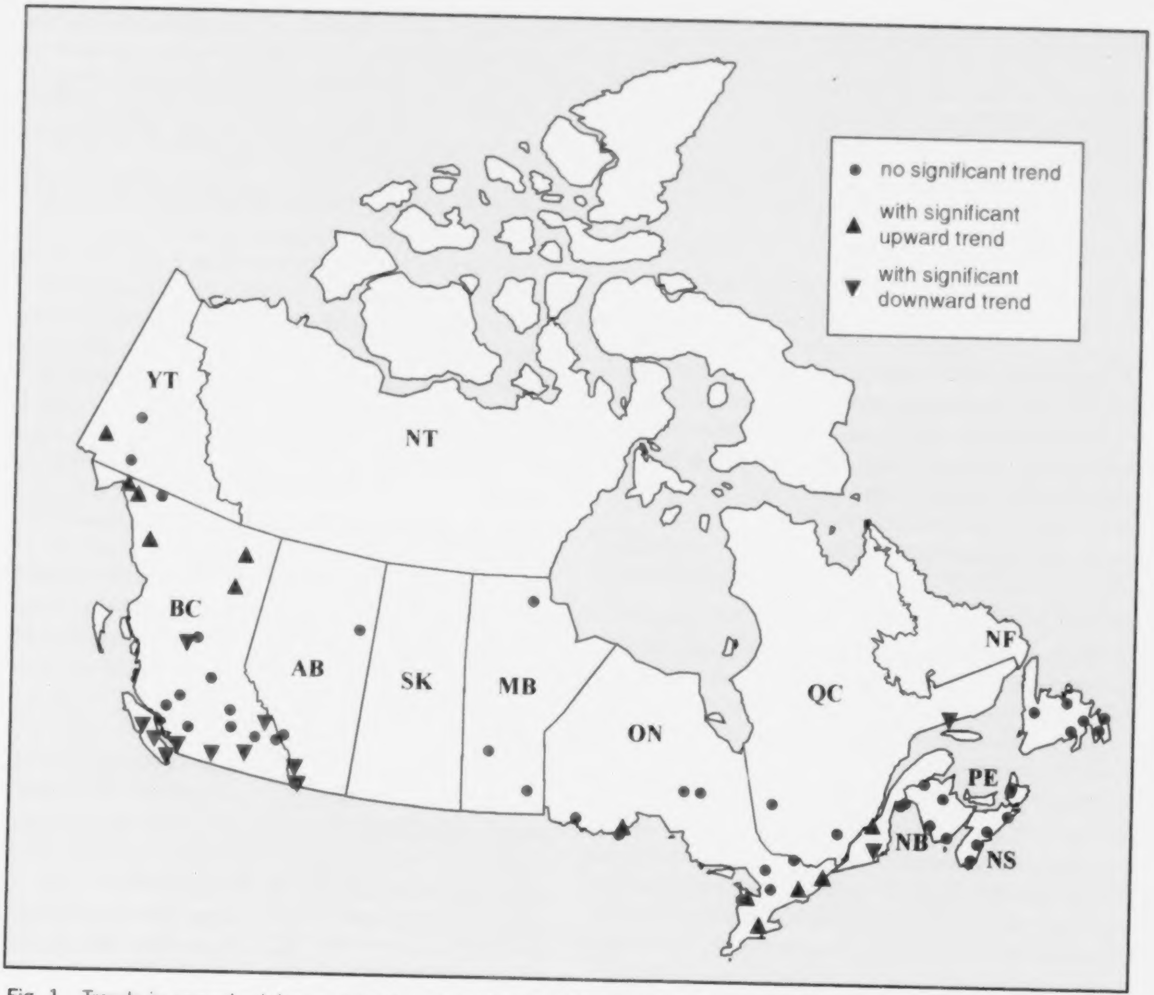
Overall, we seem to be addressing some important issues and making progress toward improving our knowledge base on water availability. However, Canadian researchers are not explicitly pursuing work aimed at increasing our understanding of water availability. There are areas in which Canada has very good knowledge of important processes, and there are other areas where there are rather obvious knowledge, information, or product gaps. Canada needs a national program that coordinates our scientific expertise, data collection, modelling, and research to position us to be able to estimate water availability and to deal with impacts of climate variability and change in streams and rivers.

Trends

The general public has become more aware of climate change and climate variability and their potential impacts on water availability. This has led to greater acceptance of the need for further study and may, in turn, lead to actions to address perceived impacts.

Concern has increased that climate change and variability might have impacts on hydrologic extremes (i.e., floods and droughts) as well as affecting the overall level of water availability. This realization has led to greater appreciation of the importance of understanding extremes of water availability and the impact change might have on society, the economy and the environment.

We do not yet know, with certainty, the impacts of climate change and variability on water bodies of importance to Canadians. Efforts are being made to define potential impacts based on generated future scenarios, in many cases based on results of one or relatively few GCMs, with different GCMs typically providing different potential future conditions. Disturbingly, the modelled impacts (i.e., prognostic analyses) tend not to be consistent with retrospective analyses of hydrological data (i.e., diagnostic analyses) for the same periods. For example, the Mackenzie Basin Impact Study (Cohen, 1998) noted that streamflow in tributaries to the


● no significant trend
▲ with significant upward trend
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YT
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Fig. 1. Trends in annual minimum daily flow data (1957-1996) for the Canadian RHBN (Yue et al., 2003).

Mackenzie will decrease with warming, but Whitfield and Cannon (2000) suggest that streamflow may initially be increasing in these same streams. There are also some signs of consistency between prognostic and diagnostic analyses, such as earlier freshets for river basins characterized by snowmelt. As long as a gap exists between the results of prognostic and diagnostic analyses, caution should be exercised when developing coping strategies and policies based on seemingly conflicting evidence.

Diagnostic studies require statistical testing methodologies. There has been a tendency to develop increasingly sophisticated approaches that more fully address limitations of earlier approaches and allow spatial inferences to be made. These approaches have led to an increased understanding of the patterns of trend in streamflow (Burn and Hag Elnur, 2002; Cunderlik and Burn, 2002; Whitfield and Cannon, 2000; Yue et al., 2002b).

However, the number of sites in various hydrological networks available for diagnostic studies is decreasing. Statistically based diagnostic studies require networks with long-term stations with adequate geographical coverage to provide the capacity to discern whether a trend is or is not occurring and where a trend might be occurring (Yue et al., 2002a). Long-term data are needed to depict and separate accurately the characteristics of natural climate variability from climate change.

Increasingly, we need a more global perspective on the driving forces generating streamflow. There has been an increased understanding of the teleconnections between large-scale oceanic and atmospheric processes and meteorological and hydrological processes. Examples of large-scale oceanic and atmospheric processes include the El Niño - Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). These processes and the impacts they can have on hydrology and, hence, water availability, are becoming better known as new research explores such relationships (Barlow et al., 2001; Neal et al., 2002).

Knowledge and Program Needs

There are significant difficulties in distinguishing between natural climate variability and long-term change. To address this issue more fully, attention must focus on three broad areas: data collection, technique development, and coordinated and funded programs.

Data Collection

As a nation, our surface water and precipitation monitoring systems are poorly resourced, designed and coordinated. For example, the World Meteorological Organization (1994) recommends minimum densities for various networks and has a minimum for precipitation observations of between 1000 and 4000 locations based upon land mass, while Canada has less than 500 reported sites (WMO, 1995). These deficiencies should be addressed for a number of reasons, including providing a solid foundation for studies directed to separating climate change effects from those of normal variability. Some key steps include:

- increasing linkages among observing networks to improve understanding of causes and effects of impacts within the hydrological cycle. For example, glacier mass balance represents an opportunity to increase the hydrologic understanding of transient changes in runoff regime (Moore and Demuth, 2001);
- conducting a thorough review and design of our observing networks to ensure they are effective and can provide adequate information upon which to base analyses. With additional investment to long-term observing systems, Canada will have the data and knowledge necessary for sound decision making;
- collecting flow and related data at additional sites in unregulated and relatively pristine watersheds to fill geographic gaps and more adequately represent smaller areas. The enhanced observation of small basins increases knowledge of the effect of scale on hydrologic processes in Canada; and
- enhancing data collection in northern Canada where the changes in local climates are predicted to be larger than in the south. With this focus, we are more likely to be able to verify that change is occurring as predicted.

Technique Development

The dilemma Canada faces with respect to climate change and variability and their associated impacts indicates the need for development of new approaches and methodologies. Current approaches are inadequate for dealing with the unprecedented ramifications of potential changes. There has been a heavy reliance on simple statistical testing approaches and GCMs. Currently, very little research effort is placed on hydrological aspects of climate change and development of statistical trend detection approaches relevant for hydrological analyses. There is a need to:

- develop statistical testing approaches to compare spatial and temporal model results with observed spatial and temporal trends; and
- develop more powerful retrospective (diagnostic) procedures.

There is also a need to develop analysis and modelling techniques to increase understanding of the impacts of climate change, natural variability and human-induced interventions. Beyond development of new modelling approaches, this necessitates obtaining data on consumptive uses, diversions, regulation and land-use changes. Remotely sensed data have tremendous potential for aiding assessment of general water availability in Canada; investments are needed to develop methodologies and capitalize on this potential. Such capabilities are fundamental to establishing current and future water availability throughout Canada. These concepts are important elements of integrated watershed management and can lead to adaptive practices that will help Canadians face changes in water availability.

To establish local trends and conditions, national, regional (e.g., hemispheric, North American), and global analyses must be performed. Patterns emerge and are uncovered when this issue is approached from different scales and perspectives. Countries should establish specialized networks with characteristics similar to those used to establish the RHBN. This provides a common basis for analysis, and for evaluating and understanding variability and change within the global, regional and Canadian contexts.

At present, hydrologists are concerned that the GCMs do not accurately reflect hydrological conditions. GCMs do not provide outputs at the temporal and spatial scales deemed important for water resources applications. There is a need to:

- improve operational modelling of Canadian hydrological systems with a particular focus on the feedbacks inherent in this system
- improve operational watershed models by inclusion of small-scale hydrological process knowledge to replicate nature's processes more closely
- move beyond using GCM outputs as inputs to hydrological models as this is an over-simplification of the hydrological cycle, given the complex feedbacks within water and energy cycles
- establish the performance of the GCM and GCM-hydrological models over known conditions, particularly with respect to replicating trends in streamflow conditions over the past 30 to 50 years to increase model credibility by closing the gap between prognostic and diagnostic analyses; and

- increase GCM resolution so that important land features known to influence local climatology, such as the Great Lakes and Rocky Mountains, are reasonably represented in the modelling system.

Previous approaches for assessing risk in hydrological systems have explicitly assumed that the hydrological regime is stationary and will continue to be stationary in the future. This assumption is not necessarily valid, due to natural variability and climate change. However, there is insufficient evidence, particularly because of a lack of data upon which to assess variability and change and from a cause-effect perspective, to warrant revisiting current design approaches. As a precaution, it would be wise to consider within risk management that future risks may be more or less than anticipated, based on a historical analysis of data. At present, it is difficult to be certain if recently observed patterns and trends will persist into the future.

Coordinated and Funded Programs

Funding currently provided for research and development on available water within Canada's streams and rivers and the influence of climate variability and change on these waters needs strengthening. Environment Canada should focus and coordinate its water programs, developing a clear direction on understanding Canada's water availability.

Research and development associated with water quantity are important for developing policy and programs to assist Canadians and their economy with this issue. Potential future impacts of variability and climate change on water availability could have tremendous impacts on society, the economy, and the environment. To ensure that Canadians are not inadvertently placed under increased risk, greater investment in ascertaining water availability is needed. Leadership is required to help focus efforts in research and development to gain a better understanding of hydrological conditions associated with natural variability, and those emanating from climate change. Emphasis should be placed on development of prediction (diagnostic and prognostic) systems for overall infrastructure design, and this would also assist in preventing loss of life and reducing damages to property and livelihood from floods and droughts.

Increased emphasis should be placed on retrospective diagnostic analysis, in addition to the current focus on generation of future scenarios and their impacts. Powerful spatial and temporal statistical testing approaches need to be developed. GCM performance requires validation with historical data, using sound statistical tools. There is a need to develop a much better understanding of the cause-effect relationships that have led to pronounced hydrological trends and patterns over recent periods. These needs accentuate the requirement for increased program coordination and funding for research and development programs. There is a need for increased data collection targeted at hydrometric stations on natural basins and for increased observation of meteorological variables to develop the knowledge and hydrological modelling capability vital to quantifying the impacts of climate on water availability.

References

Adamowski, K. and C. Bocci. 2001. Geostatistical regional trend detection in river flow data. Hydrolog. Processes 15: 3331-3341.

Barlow, M., S. Nigam and E.H. Berbery. 2001. ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and stream flow. J. Climate 14: 2105-2127.

Burn, D.H. and M.A. Hag Elnur. 2002. Detection of hydrologic trend and variability. J. Hydrol. 255: 107-122.

Buttle, J.M., G. Jones, P. Marsh and M.K. Woo. 2000. Recent advances in Canadian hydrology. Hydrolog. Processes 14: 1537-1538.

Cohen, S. 1998. Mackenzie basin impact study (MBIS). Environment Canada, No. En 50-118/1997-1E, 1998.

Cunderlik, J.M. and D.H. Burn. 2002. Local and regional trends in monthly maximum flows in southern British Columbia. Can. Water Resour. J. 27: 191-212.

Harvey, K.D., P.J. Pilon and T.R. Yuzyk. 1999. Canada's reference hydrometric basin network (RHBN). *In* Proceedings of the CWRA 51st Annual Conference, Nova Scotia.

Kite, G.W. 1995. The SLURP model, computer models of watershed hydrology, chapter 15. *In* V.P. Singh (ed.), Water Resources Publications, Littleton, Colo.

Kouwen, N. and S.-F. Mousavi. 2002. WATFLOOD/SPL9 hydrological model and flood forecasting system, chapter 15, p. 649-686. *In* V.P. Singh and D.K. Frevert (ed.), Mathematical models of large watershed hydrology. Water Resources Publications, Littleton, Colo.

Lins, H.F. and J.R. Slack. 1999. Streamflow trends in the United States. Geophys. Res. Lett. 26(2): 227-230.

Moore, R.D. and M.N. Demuth. 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climatic fluctuations. Hydrolog. Processes 15: 3473-3486.

Neal, E.G., M.T. Walter and C. Coffeen. 2002. Linking the pacific decadal oscillation to seasonal discharge patterns in Southeast Alaska. J. Hydrol. 263: 188-197.

Pilon, P.J. and J.K. Kuylenstierna. 2000. Pristine river basins and relevant hydrological indices: essential ingredients for climate-change studies. WMO Bulletin 49(3): 248-255.

Pilon, P.J. and S. Yue. 2002. Detecting climate-related trends in streamflow data. Water Sci. Technol. 8(45): 89-104.

Whitfield, P.H. and A.J. Cannon. 2000. Recent variation in climate and hydrology in Canada. Can. Water Resour. J. 25: 19-65.

World Meteorological Organization (WMO). 1994. Guide to hydrological practices. Fifth Edition. WMO-No. 168. Table 20.1, p. 270.

World Meteorological Organization (WMO). 1995. INFO-HYDRO manual. WMO-No. 683. Table 4.4.07.

Yue, S., P.J. Pilon, G. Cavadias and B. Phinney. 2002a. Power of the Mann-Kendal and Spearmans rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 259: 254-271.

Yue, S., P.J. Pilon and B. Phinney. 2003. Canadian streamflow trend detection: impacts of serial and cross correlation. J. Hydrol. Sci. 48(1): 51-64.

Yue, S., P.J. Pilon, B. Phinney and G. Cavadias. 2002b. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrolog. Process. 16(9): 1807-1829.

Zhang, X., K.D. Harvey, W.D. Hogg and T.R. Yuzyk. 2001. Trends in Canadian streamflow. Water Resour. Res. 37(4): 987-998.

Chapter 12

CLIMATE VARIABILITY AND CHANGE – LAKES AND RESERVOIRS

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Current Status

A lake is generally defined as an inland body of fresh or saline water, appreciable in size (i.e., larger than a pond), and too deep to permit vegetation (excluding submergent vegetation) to take root completely across its expanse. It is estimated that Canada has more than a million lakes that cover 7.6% of the country's area. Nearly 14% of the world's lakes with surface areas over 500 km^2 are located in Canada. There are 578 lakes greater than 100 km^2 (Canadian National Committee, 1975). Substantial amounts of water (not accurately quantified) are contained in small to medium sized lakes and there are more than 900+ major reservoirs (see Chapter 2). A wide range of lake types is contained within 5 major drainage basins in Canada (Fig. 1). These include such lakes as the Laurentian and Mackenzie Great Lakes, arctic and sub-arctic lakes, glacial, boreal, perched, prairie, shallow enclosed saline lakes and reservoirs. Other than for selected large and smaller lakes, there is a lack of knowledge on basic details of the morphology and hydrologic responses of Canadian lakes, especially in Canada's vast northern regions. It is estimated that Canada has approximately 20% of the world's existing freshwater reserves, yet such uncertainties and a lack of a detailed regional lake inventory make it difficult to assess accurately the availability of clean freshwater. This is critical since an understanding of the complexities of water quality and ecosystem health is often linked to the supply of freshwater.

Lakes and reservoirs are important sources of water for a range of socio-economic uses such as municipal water supply, irrigation, industrial processes, and recreation. As the Canadian population grows, demands for clean freshwater will certainly increase, and a critical issue is the effect of climate variability and climate warming on the availability of clean freshwater from lakes and reservoirs. This Chapter provides an overview of critical stresses on Canada's freshwater supply and the vulnerabilities associated with these stresses, and it provides an assessment of the response of lakes and reservoirs to climatic variability and climate warming, using selected examples of lake and reservoir types in different regions of Canada.

Current Stressors and Vulnerability of Lakes and Reservoirs

Canadian water resources in lakes and reservoirs are becoming increasingly vulnerable to a range of stresses, both natural and human-induced (Bruce et al., 2000). For example, natural stresses include increased climate variability and extremes that can affect both the magnitude and seasonal cycles of water budget components that influence the availability of clean freshwater. Climate extremes (e.g., El Niño, and large-scale weather systems with high winds and precipitation) have been shown to significantly affect lake heat storage, temperature and evaporation (Rouse et al., 2003; Schertzer et al., 2000).

Human-induced stressors such as increasing consumptive use of water are often linked to regions with significant growth in population. These stressors have the effect of lowering lake levels and reducing downstream flows, a major area of concern because of adverse economic and environmental impacts associated with progressive lowering of water levels. The current total per capita consumptive water use in Canada is approximately 350 litres per person per day.

Basin to basin diversion of water also affects flows in each basin. For example, on the Great Lakes (Fig. 2), there are currently five major diversions, or water re-routings, on the Laurentian Great Lakes (i.e., Long Lac and Ogoki diversions, the Chicago diversion, the Welland Canal, and the New York State Barge Canal) and two regulation points (Sault Ste. Marie and Cornwall). These diversions affect long-term Great Lakes water levels, and in some cases have an effect on pollution dilution.

Historically, there have been significant changes in water levels in the Great Lakes caused by climate variability (Fig. 3). Both high and low water levels have resulted in problems: high water levels cause shoreline erosion, resulting in significant infrastructure and economic costs related to replacement and maintenance of recreational properties and shoreline protection, while low lake levels affect navigation, recreation, hydro generation,

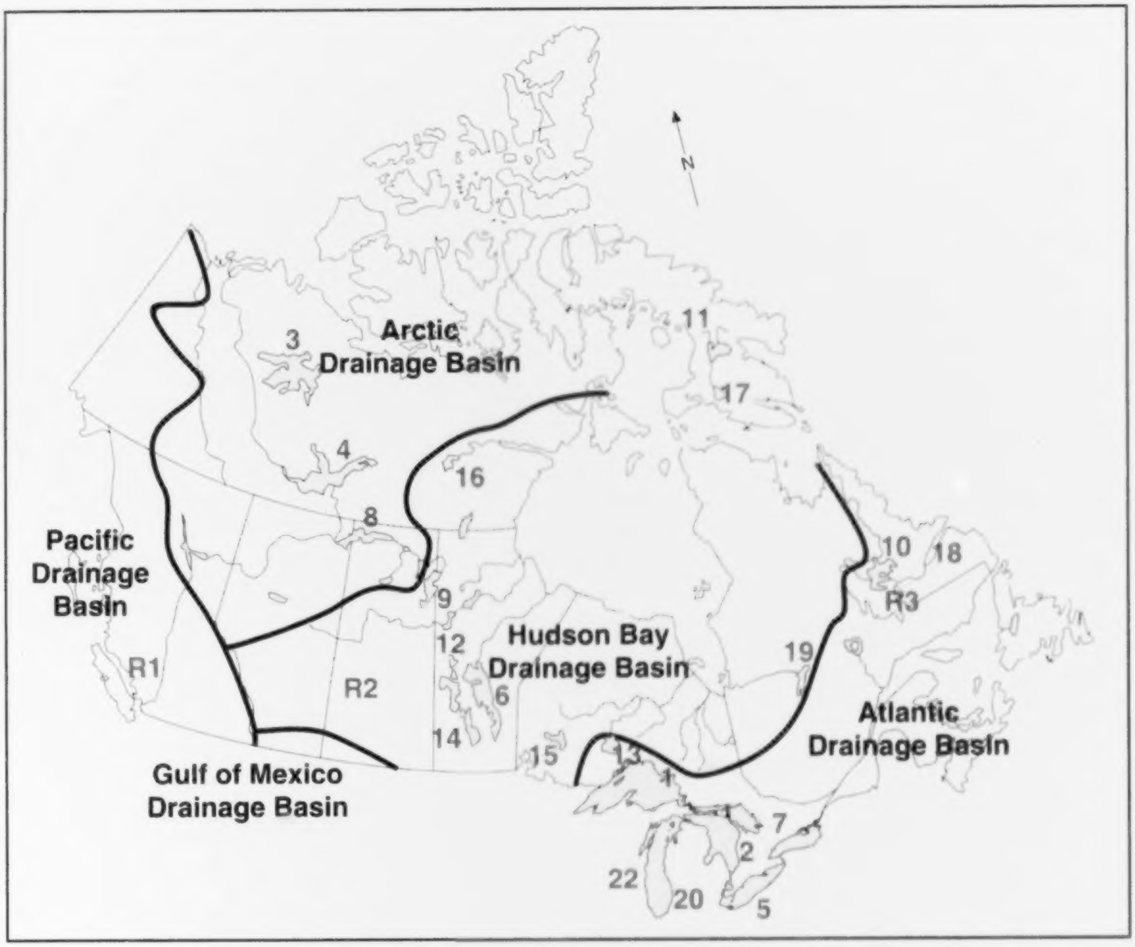

Fig. 1. Location of major drainage basins, distribution of the 20 largest lakes (>1000 km²) in Canada, and location of selected reservoirs.

Selected Lakes			
1. Superior	2. Huron	3. Great Bear	4. Great Slave
5. Erie	6. Winnipeg	7. Ontario	8. Athabasca
9. Reindeer	10. Smallwood	11. Nettling	12. Winnipegosis
13. Nipigon	14. Manitoba	15. Lake of Woods	16. Dubawnt
17. Amadjuak	18. Melville	19. Mistassini	20. St. Clair
22. Lake Michigan (entirely in U.S.)			

Selected Reservoirs		
R1. Vancouver	R2. Lake Diefenbaker	R3. Churchill Falls

and ecosystem and health problems. Shallow water adversely affects navigation in the lakes' connecting channels. To maintain channel depth, dredging has been necessary in the St. Mary's River, Lake St. Clair and elsewhere.

Water export has been an issue with potential to affect water availability. Canada sells bottled water to other countries, but shipments of bulk water are currently not allowed.

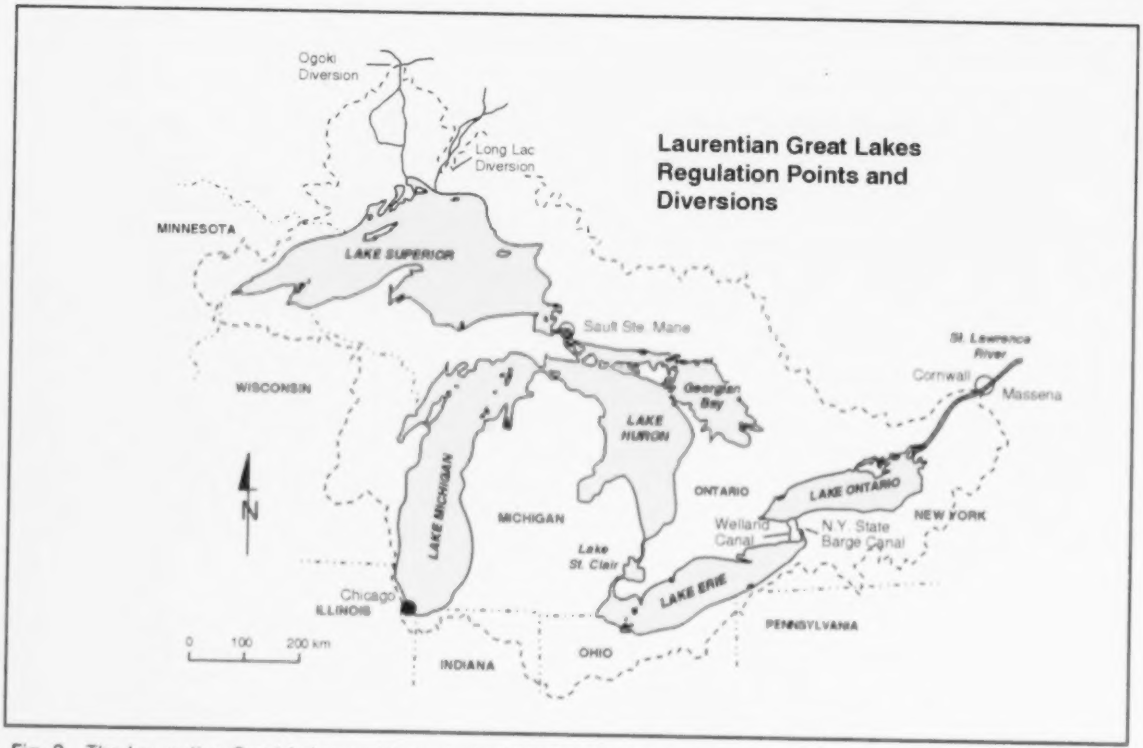

Fig. 2. The Laurentian Great Lakes and the extent of the Great Lakes basin in Canada and the U.S. Water regulation points are depicted at Sault Ste. Marie and at Cornwall. Water diversions occur at Ogoki, Long Lac, Chicago, Welland Canal and New York State Barge Canal.

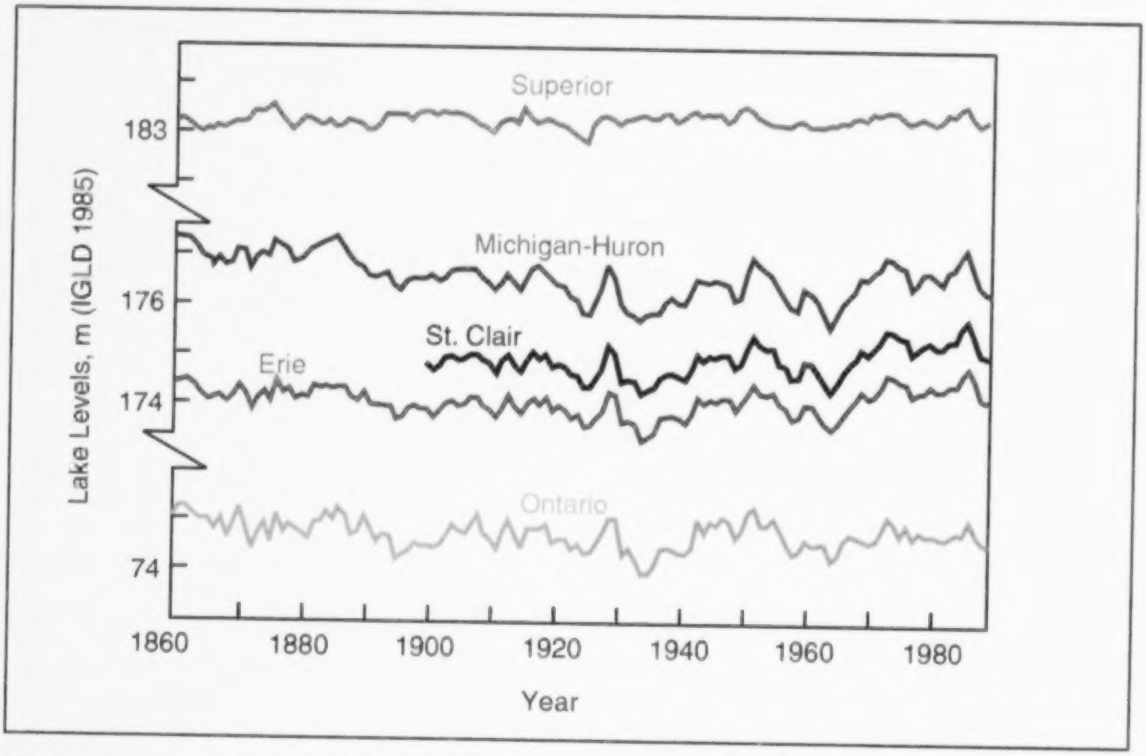

Fig. 3. Long-term annual water level fluctuations for the Laurentian Great Lakes for 1960 to 1990 referenced to the International Great Lakes Datum (IGLD) in 1985 (adapted from Croley, 1995).

Water supply in reservoirs is affected both by climate variability and supply and demand pressures. Often the freshwater supply in lakes is affected by competing uses (e.g., increase minimum flows for downstream recreation and fish habitat). The stressors are often cumulative, posing increased threats for water availability. Other stressors include habitat and watershed modification and land-use changes. Vandalism and terrorism are ongoing security concerns that can adversely affect the availability of clean freshwater. Maintaining access to the use of water through trade agreements and aboriginal rights also challenges water availability.

Lakes and reservoirs vary in their susceptibility to stressors. For example, there are different concerns related to large deep lakes compared to smaller lakes. There is a range of management involvement for lakes in various regions of Canada. In unmanaged systems there are no structures in place to buffer effects of hydrologic variability on water supply. Although concerns differ for lakes in the various regions of Canada, unmanaged water systems, and systems that are currently stressed or are inadequately managed, are the most vulnerable.

Trends

Climate Change Projections, Impacts and Responses

A wide array of climate change scenarios arise from global climate models. A clear warming trend is indicated in these scenarios. However, the models do not always agree in the magnitude or direction of other components, especially precipitation. Currently, one uncertainty in impacts on lakes results from a lack of coupling between atmospheric and lake processes. All lakes and reservoirs in Canada will be affected by climate change. The following discussion provides examples of likely responses to climate variability and change.

Estimated to number over one million, Canada's lakes are important for irrigation, industrial processes, municipal water supply and recreation.

Response of Large Lakes: The Laurentian Great Lakes are a source of freshwater for 45 million people. Historical concerns have been focussed on water quantity and water quality. Research is in progress to understand potential impacts of climate variability and change on these lakes. Climate analogs, climate transpositions, and General Circulation Model (GCM)-based climate scenarios in steady-state or transient modes have been applied (e.g., see Schertzer and Croley, 1999). Table 1 shows an example of a transient climate scenario result. According to this model, the over-lake meteorological conditions are conducive to increased annual lake evaporation in all lakes. Net basin supplies, defined as precipitation + runoff - evaporation, are projected to increase in Lake Superior. However, net basin supply to the downstream lakes shows large decreases, and Lake St. Clair shows a dramatic reduction. In all cases, this simulation suggests that climate warming will have the effect of reducing lake levels. Other simulations, (e.g., the Canada Centre for Climate Modelling and Analysis and Hadley GCMs), show increases and decreases in Great Lakes water levels (Mortsch et al., 2000). While some simulations show lake level increases, they are not greater than those resulting from natural variability. Despite the uncertainty exhibited in these simulations, there is general agreement about probable reductions of lake levels under climate warming. This creates concern that the Laurentian Great Lakes will have less available water to meet projected increases in future demands for navigation, consumption, diversions and water export.

Some of the largest recent temperature increases anywhere in the world have been observed in the Mackenzie basin (Stewart et al., 1998). All of the large lakes of the Mackenzie basin are ice dominated into June and often until the summer solstice. With earlier ice melting, more solar energy can be used to heat the lakes during spring, resulting in higher heat storage (Schertzer et al., 2000). This energy starts to return to the atmosphere as evaporative and convective heating in mid- to late-summer. The convective fluxes reach a peak in fall or early winter, well after the terrestrial surfaces and smaller lakes are frozen. Climate warming would result in earlier spring ice melt, greater solar heating and more evaporation that would persist longer into the subsequent winter. That such changes can happen in a time span of one year is shown definitively by Blanken et al. (2000).

Most of the large lakes in Canada are components of very large drainage basins that can be affected by events far upstream, such as flow regulation (see Chapter 2). For example, Lake Winnipeg receives water

Table 1. An example of a transient climate scenario simulation for selected variables using the Goddard Institute for Space Studies model to assess potential climate change impacts on the Laurentian Great Lakes (modified from Croley, 1995)

Hydrological Variable	Basin (mm/decade)					
	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Annual Basin Precipitation	+24	+7	+2	-0	+3	+1
Annual Basin Evaporation	+25	+14	+12	+15	+16	+16
Annual Basin Runoff	+4	-7	-9	-15	-15	-14
Annual Lake Evaporation[a]	+18	+19	+22	+38	+40	+24
Annual N.B.S.[a]	+17	-27	-41	-245	-75	-75
Annual Net Outflow[a]	+20	-31	-31	-241	-70	-57[b]
Lake Level	-13	-59	-59	-64	-66	-93[b]

[a] N.B.S. = precipitation + runoff - evaporation, expressed as a depth over the lake.

[b] Computed over first 7 decades since Ontario regulation plan fails in the eighth.

input from the Saskatchewan River. Most of the Saskatchewan River is in a negative water balance situation during summer, its flow being sustained by snow and glacial melt in the Rocky Mountains. Climate warming, thus, will affect rates of snow and glacial melt in the mountains and the dynamics of the input of water into Lake Winnipeg.

Response of Smaller Lakes: Large-scale maps of Canada show areas that seem devoid of lakes but in fact there is a range of smaller lakes and ponds everywhere over the Canadian landscape (Allan et al., 1994). Many of these lakes, especially in the North, are particularly sensitive to climate change. Characteristics of small lake responses to climatic variability and change are provided below for a range of lake types.

The Mackenzie River basin has a myriad of lakes of all sizes, especially within the Canadian Shield. Here the annual evaporation ratios of (land : small lake : medium size lake : large lake) is approximately (1 : 1.28 : 1.65 : 2.11) illustrating that lakes are very efficient evaporating systems, and that the larger the lake the more it evaporates (Rouse et al., 2002). Small lakes can double their evaporation totals under very warm and sunny conditions and Great Slave Lake can increase its seasonal evaporation by 28% (Blanken et al., 2000) during intense El Niño warm events. Thus evaporation from lakes of all sizes is highly sensitive to climate warming. The larger the lake the greater the seasonal lag in evaporation. A small shallow lake's evaporation closely follows the solar radiation and air temperature cycle peaking in early July, whereas a deep lake, such as Great Slave Lake, lags small lakes by about three months with evaporation peaking in late fall and early winter. Unfortunately, climate warming would have an uncertain feedback effect on, for example, cloudiness and receipt of solar energy at the earth's surface in different regions of Canada.

Approximately 60% of the 25,000 lakes in the Mackenzie River Delta are perched above the main distribution channel. These lakes generally have a negative water balance between flooding events, which are further influenced by the timing of rain and snow events. Ice jam breakup releases floodwater into these lakes in the spring. This occurs every five years on average and in the interim many lakes dry up. Climate warming will affect the dynamics of these lakes. Marsh and Lesack (1996) show a more negative water balance under 2 x CO_2 scenarios. To model changes in the ice-jam flooding, there is a great need for an improved ability to simulate discharge of the Mackenzie River and the occurrence of ice jams.

In a study of boreal lakes in northwestern Ontario, Schindler et al. (1996) showed that from the 1970s to the 1990s, despite considerable interannual variability, there was an increase of air temperature (+1.6°C), a general decline in precipitation (~60% of highest years), an increase in evaporation (~50%) and an increase in annual solar radiation. The net effect of precipitation and evaporation changes resulted in decreased streamflow, with annual runoff declining significantly from ~400 to <150 mm yr^{-1} by the late 1980s. The combined effects resulted in longer water renewal times for lakes. Lakes became warmer during the period with deeper epilimnions as thermoclines lowered by ~1.5 m. The average ice-free season also increased by ~15 days, with significantly earlier ice-melt. Changes in weather and hydrology also influences the basin chemical exports to the lakes, thus influencing in-lake processes, lake chemistry and biological components.

Climatic change impacts will differ for lake types such as arctic, sub-arctic, boreal, and glacial lakes and prairie sloughs. With climate warming, high arctic and high alpine lakes that currently do not melt completely, can potentially become totally ice free during the summer. This will change their annual water budgets. Enhanced melting of permafrost can make some northern lakes vulnerable to catastrophic drainage through existing frozen water channels. Warmer conditions will result in greater glacial melt and runoff, affecting the water balance dynamics of glacial and glacial-fed lakes. At present, many prairie sloughs are ephemeral. If, as indicated by many climate scenarios, prairie regions suffer from accentuated drought conditions, more of these ponds will become ephemeral and those currently under stress will disappear, reducing water availability for livestock watering and waterfowl habitat. Snowmelt-dominated watersheds will experience changes in timing and magnitude of peak flows and reductions in low flows, which will affect lake water levels. Changing water table depth in response to hydrological changes can affect aquifers and groundwater-fed lakes. If there is a greater frequency of high intensity rains, small watershed runoff is likely to have higher peak discharges. This may threaten dam and reservoir integrity resulting in increased bank erosion, sediment loads to lakes, and short-term effects on lake water levels.

Response of Reservoirs: The number of reservoirs in Canada is steadily increasing (see Chapter 2). In general, these sources of freshwater are used for municipal consumption, for agriculture and for power generation in areas that do not have access to large lakes. Reservoirs range in size and can be either single- or multiple-watershed systems. Water availability is related both to the gains and losses from the reservoir itself and from its watershed. The following provides examples of the response of these reservoirs to climate variability and potential responses due to climate warming. Selected examples include the Greater Vancouver (British Columbia) reservoir, which is a multi-watershed system; the dam and reservoir system of the Grand River basin (Ontario); Lake Diefenbaker (Saskatchewan), which is a constructed lake; and a large-scale reservoir such as Churchill Falls (Labrador), used for hydroelectric generation.

The Greater Vancouver Regional District obtains its water supply for 2 million people from three forested watersheds in the Pacific south-coast mountains. Planning for the water supply has been based upon the previous 100-year climate records, whereby significant winter precipitation creates a large snowpack. The reservoirs are maintained at full pool by precipitation and snowmelt runoff well into summer. After snowmelt, reservoir pool levels decrease into late summer and are eventually replenished by fall storms. Climate change predictions for the Pacific south-coast region are for intense storms, and warmer annual temperatures that could reduce the snowpack thereby extending the dry summer conditions. These changes would increase the water consumer demand during a longer summer period, when the reservoir inflows are less than the outflows for consumption and downstream requirements, thus causing extremely low water levels in the reservoirs. This predicted scenario indicates a threat to the availability of a reliable water supply for the Vancouver region that could necessitate implementing additional conservation measures and water restrictions, expanding existing reservoirs, and developing additional water supply sources. Predicted climate changes create uncertainties regarding the ecological integrity of terrestrial and aquatic ecosystems. Climate change scenarios suggest intense winter storms that could lead to a higher frequency and magnitude of landslides. Longer, drier summers could also increase the frequency and magnitude of wildfire. New species, such as invasive insects, may affect forest health. These ecosystem disturbances release sediment and nutrients that are suspended in the runoff and delivered into the reservoirs. Increased nutrients and sediments, coupled with low water levels that may be unseasonably warm, could initiate changes to the aquatic ecology within shallow reservoirs, resulting in eutrophication and undesirable water quality parameters (Hamilton et al., 2001). The water supply system is designed according to historical water quality parameters. Significant changes in the source water quality could render a source unusable for a period of time, creating increased supply demands on alternative water reservoirs.

Originally, the dam and reservoir systems on the Grand River were primarily designed for spring flood control; however, over the years the operations have expanded to include low flow augmentation, habitat preservation, and recreation. Historically with "normal" spring operation, the reservoirs are filled by melting snowpack and rain events in the watershed. In recent years, lack of snowfall, warm winter temperatures, and winter rain have contributed to a sparse snowpack and a small spring freshet. Traditional management practices have had to be modified, in part, due to changing climatic conditions – lack of snowcover and earlier melt combined with warm, dry summer weather with high water demands and evaporation losses. The spring filling of the reservoirs has commenced sooner to store water from an earlier spring melt and to retain it in anticipation of low flow conditions in summer and fall. However, with this practice the system becomes vulnerable to flooding if late spring snowfall or rainfall events occur and reservoirs are filled to near capacity. The risk is accepted so that low summer base flows can be augmented by stored reservoir water in order to maintain fisheries habitat, assimilative capacity, recreation, and aesthetics.

Lake Diefenbaker represents a reservoir in central Saskatchewan with a negative water balance. The reservoir is supplied by the South Saskatchewan River. During drought years, the water supply is restricted and evaporation is enhanced, resulting in declining water levels. This is exacerbated by consumptive water use (e.g., irrigation and livestock watering), so that multiple stressors are at work in dry conditions. Climate warming might be expected to enhance evaporation from the reservoir and its watershed. If not compensated for by enhanced precipitation, severe water depletion would result.

The Smallwood Reservoir in Labrador is the largest reservoir in Canada, providing water to the Churchill Falls hydroelectric plant. The electricity output supplies 20% of Quebec's total needs. The reservoir covers 5698 km^2, with a water storage of 29×10^9 m^3. The reservoir was formed in bog and muskeg areas, and its drainage area includes much of western and central Labrador. On an annual basis, the drainage basin receives an average of 765 mm of precipitation. Long-term changes in magnitude and timing of rainfall and snowfall over the basin would affect overall generation capability. However, electric power systems may be able to adjust their operating practices to adapt to such changes. With climate change, some simulations suggest that the Churchill River will have higher spring and lower summer flows in response to changes in basin hydrology. Potential consequences include problems with turbine capacity during early spring peak flows and less hydroelectric generating capacity in summer to cope with greatest market demand.

Impacts on Seasonal Cycles and In-Lake Processes

The availability of clean freshwater in lakes and reservoirs is influenced by hydrodynamic and thermodynamic processes (Schertzer, 1997). Such processes as thermal stratification, water movements and ice cover are influenced by weather and are largely associated with redistribution of water within the lake (Lam and Schertzer, 1999). Thermal regimes in lakes are found to be most prone to climatic variability (e.g., McCormick and Lam, 1999). Higher water temperature and thermal stratification combined with available nutrients affects the degree of dissolved oxygen in lakes and reservoirs (Lam et al., 1987). Lakes and embayments that currently experience anoxia will be further stressed by higher temperatures and longer stratification periods under climatic warming (e.g., Schertzer and Sawchuk, 1990). Long-term effects of weather on seasonal and interannual patterns of water movements in large lakes is uncertain (Beletsky et al., 1999). Simulations from GCMs, or data from extreme warm or cold years, show that prolonged stratification would increase duration and magnitudes of density driven currents. Ice cover duration on lakes is particularly important since it effectively decouples the lake from the overlying atmosphere. Records for the Laurentian Great Lakes and large lakes of the Mackenzie basin show significant increases in ice-free season associated with intense El Niño events (Assel, 1999; Walker et al., 1999). Significant reduction in ice cover will result in higher lake temperatures and evaporation contributing to lower water levels.

Impact of Other Stressors Affected by Climate Changes

Increasing population in Canada will result in increased consumptive pressures on lakes and reservoirs. Projected climatic warming at levels that result in severe decreases in water levels in connecting channels of the Great Lakes will require an increase in dredging to maintain viable shipping to and from major industrial centres in the Great Lakes. Diversion of water from large deep lakes has long been a controversial issue since diversion without augmented flow poses risks of long-term reductions in lake water levels. Severe drought in central regions of North America will likely result in increased pressure to divert water from Canada's Great Lakes and extensive lake-river systems to alleviate lowering water tables in drier areas of North America. Freshwater is a valuable resource that is not uniformly distributed over the globe. Climate warming is likely to increase drought conditions in many parts of the world. Canada is viewed as having large reserves of freshwater, and increasing international pressure for water export from lakes would reduce available reserves in Canada. Industrial and manufacturing production is likely to increase in the Laurentian Great Lakes region. Currently, the Great Lakes - St. Lawrence River system is used extensively for hydroelectric production and commercial navigation. Under high evaporation–low precipitation scenarios there will be reductions in water levels and connecting channel flows that would adversely affect such economic activity. Greater conflicts among users is expected to increase as water availability to meet multiple use demands decreases. Binational water management may become more difficult due to reduction in water supply and increased future demands for freshwater. This may require adjustment of formal and informal criteria and legal instruments used for managing binational water resources. Climate warming impacts that reduce the availability of freshwater in lakes will also have social implications such as the responsibility to ensure that agreements with aboriginal populations on water availability and quality are met. The cumulative impact of these stressors will be worsened as a result of climate warming.

Knowledge and Program Needs

To ensure the viability and availability of clean freshwater in Canada there are specific knowledge requirements and program needs, as follows.

Climate-Hydrological Responses

- ***Monitoring and Databases:*** Monitoring of such factors as seasonal changes in hydrological characteristics of lakes in response to climatic change is required to reduce knowledge gaps and uncertainties relating to climate impacts on lakes and reservoirs. Long-term case studies over a range of lakes and regions is a possible approach. Monitoring is critical to develop historical databases to detect changes in water resource availability.
- ***Lake and Reservoir Inventory:*** Better documentation on lake surface areas and volumes, as well as seasonal changes, is required on lakes in Canada, especially in the North. Current remote sensing capabilities can be utilized to quantify dynamic changes in lakes in response to climate variability and change.
- ***Process Modelling:*** Improved understanding of lake processes is required to understand potential responses to environmental and human-induced stressors. Research is required for advance in the following areas:
  - hydrological budget models applied to lakes, reservoirs and basins of Canada
  - development of coupled lake-atmosphere models to improve regional climate simulations
  - development of improved climatic change scenarios at smaller (lake) scales
  - understanding climatic feedbacks in different regions of Canada
  - assessments of uncertainty and risk evaluation, and
  - improving management decision models – testing of mitigation and adaptation options.

Climate Warming and Freshwater Ecosystem Linkages

- ***Water Quality:*** Research is required to understand the impacts of water level changes and warmer water temperatures on lake pollution, dissolved oxygen concentrations, sedimentation rates, and nutrient concentrations.
- ***Human Health Effects:*** More needs to be learned about the possible consequences of less water and warmer temperatures on in-lake bacteria, including taste and odour levels, which can affect human health.
- ***Ecosystem Integrity:*** Climatic changes will have an impact on biodiversity and habitat within freshwater lakes. There is potential for significant effects on aquatic biota in both commercial and sport fisheries. There are knowledge gaps in understanding climate effects on aquatic ecosystem components.
- ***Socio-economic Impacts:*** Lakes and reservoirs in Canada have been used for drinking water, navigation, recreation, and hydro generation. Integrated assessments of vulnerabilities to, impacts of, and adaptive capacity for responding to water supply changes are required. Similarly, advances in lake and reservoir process models and climatic scenarios are required to assess future freshwater availability for socio-economic demands.
- ***Freshwater Demands:*** Population growth will result in greater demand for freshwater for municipal, industrial and agricultural consumption. Lakes and reservoirs along with groundwater are sources that will be used to meet these demands. Research is required to understand the limitations of Canadian freshwater sources to meet future demands.

Requirements for Effective Management

- ***Strategy Development:*** We need to identify and assess adaptation strategies to lessen vulnerabilities to water supply changes.
- ***Uncertainty Assessment:*** Research is required to evaluate uncertainties relating to data and model simulations, as well as risks and benefits of management strategies.
- ***Integrated Approaches for Water Supply:***
  - supply capacity approaches (e.g., increasing reservoir storage), and
  - demand-side approaches (e.g., differential pricing, public awareness campaigns, statutory requirements, water conservation measures by all users).
- ***Water Allocations:*** Improved methods are required for assessing instream ecological requirements, monitoring water use, and effective allocation of water within basins and provinces. More needs to be done to determine priority water uses and identify jurisdictions that take instream ecosystems into account.

Emerging Issues

- Assessing environmental, social, economic and policy implications of greater demands for water use in the basin (e.g., inland areas using pipelines for Great Lakes drinking water) as well as interbasin diversions and bulk transfers of water, especially export of water out of Canada.
- Enhancing lake and reservoir protection and security.
- Optimizing water supply through better routing among reservoirs and lakes and timing of hydrological events.
- Improving Regional Climate Models and climate change predictions on Canada's water supply by development and implementation of coupled lake-atmosphere models.
- Assessing the impact of changes in Canada's freshwater supply in lakes on the vulnerability of aquatic ecosystems, water quality and power generation.
- Investigating innovative use of water resources such as using hypolimnetic water from large deep lakes for municipal/industrial cooling processes.

References

Allan, R.J., M. Dickman, C.B. Gray and V. Crombie. 1994. The book of Canadian lakes. The Canadian Association on Water Quality, Monograph Series No. 3., Gloucester, Ontario, Canada. 598 p.

Assel, R.A. 1999. Great Lakes ice cover, Chapter 6, p. 1-18. *In* D.C.L. Lam and W.M. Schertzer (ed.), Potential climate change effects on Great Lakes hydrodynamics and water quality. American Society of Engineers, ASCE Press, Reston, Virginia, U.S.A. 232 p.

Beletsky, D., K.K. Lee and D.J. Schwab. 1999. Large-scale circulation, Chapter 4, p. 1-34. *In* D.C.L. Lam and W.M. Schertzer (ed.), Potential climate change effects on Great Lakes hydrodynamics and water quality. American Society of Engineers, ASCE Press, Reston, Virginia, U.S.A. 232 p.

Blanken, P.D., W.R. Rouse, A.D. Culf, C. Spence, L.D. Boudreau, J.N. Jasper, B. Kotchtubajda, W.M. Schertzer, P. Marsh and D. Verseghy. 2000. Eddy covariance measurements of evaporation from Great Slave Lake, Northwest Territories, Canada. Water Resour. Res. 36(4): 1069-1078.

Bruce, J.P., I. Burton, H. Martin, B. Mills and L. Mortsch. 2000. Water sector: vulnerability and adaptation to climate change. Final report prepared for Natural Resources Canada, Climate Change Action Fund. Global Change Strategies International Inc. and Meteorological Service of Canada, Ottawa. 144 p. http://www.gcsi.ca/downloads/ccafwater.pdf.

Canadian National Committee (CNC). 1975. Canadian survey on the water balance of lakes. International Hydrological Decade Report. Environment Canada, Ottawa.

Croley II, T.E. 1995. Laurentian Great Lakes dynamics, climate and response to change, p. 252-296. *In* H.R. Oliver and S.A. Oliver (ed.), The role of water and the hydrological cycle in global change. Springer-Verlag, New York.

Hamilton, S., N. Crookshank and D.C.L. Lam. 2001. Hydrologic and hydraulic routing and decision support in the Seymour Watershed, final report for Greater Vancouver Regional District Watershed Management Branch. Joint Report by Environment Canada - National Research Council/Canadian Hydraulics Centre, Ottawa. 96 p.

Lam, D.C.L. and W.M. Schertzer (ed.). 1999. Potential climate change effects on Great Lakes hydrodynamics and water quality. American Society of Engineers, ASCE Press, Reston, Virginia, U.S.A. 232 p.

Lam, D.C.L., W.M. Schertzer and A.S. Fraser. 1987. A post-audit analysis of the NWRI nine-box water quality model for Lake Erie. J. Great Lakes Res. 13(4): 782-800.

Marsh P. and L.F.W. Lesack. 1996. The hydrological regime of perched lakes in the Mackenzie Delta: potential responses to climate change. Limnol. Oceanogr. 41(5): 849-856.

McCormick, M.J. and D.C.L. Lam. 1999. Lake thermodynamics, Chapter 3, p. 1-17. *In* D.C.L. Lam and W.M. Schertzer (ed.), Potential climate change effects on Great Lakes hydrodynamics and water quality. American Society of Engineers, ASCE Press, Reston, Virginia, U.S.A. 232 p.

Mortsch, L., H. Hengeveld, M. Lister, B. Lofgren, F. Quinn, M. Slivitsky and L. Wenger. 2000. Climate change impacts on the hydrology of the Great Lakes – St. Lawrence System. Can. Water Resour. J. 25(2): 153-179.

Rouse, W.R., C.M. Oswald, J. Binyamin, C. Spence, W.M. Schertzer and P.D. Blanken. 2003. Interannual variability of the surface energy balance and temperature of central Great Slave Lake. J. Hydrometeor. 4: 720-730.

Rouse, W.R., C.J. Oswald, C. Spence, W.M. Schertzer and P.D. Blanken. 2002. Cold region lakes and landscape evaporation, p. 37-42. *In* P. di Cenzo and L. W. Martz (ed.), Proceedings of the 2nd GAME-MAGS Joint International Workshop, GEWEX-MAGS Secretariat.

Schertzer, W.M. 1997. Fresh water lakes, Chapter 6, p. 124-148. *In* W.G. Bailey, T.R. Oke and W.R. Rouse (ed.), Surface climates of Canada. McGill-Queens University Press. 369 p.

Schertzer, W.M. and T.E. Croley. 1999. Climate and lake responses, Chapter 2, p.1-74. *In* D.C.L. Lam and W.M. Schertzer (ed.), Potential climate change effects on Great Lakes hydrodynamics and water quality. American Society of Engineers, ASCE Press, Reston, Virginia, U.S.A. 232 p.

Schertzer, W.M., W.R. Rouse and P.D. Blanken. 2000. Cross-lake variation of physical limnological and climatological processes of Great Slave Lake. Phys. Geog. 21: 385-406.

Schertzer, W.M. and A.M. Sawchuk. 1990. Thermal structure of the lower Great Lakes in a warm year: Implications for the occurrence of hypolimnion anoxia. Trans. Amer. Fish. Soc. 119(2): 195-209.

Schindler, D., S. Bayley, B. Parker, K. Beaty, D. Cruikshank, E. Fee, E. Schindler and M. Stainton. 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, Northwestern Ontario. Limnol. Oceanogr. 41(5): 1004-1017.

Stewart, R.E., R.W. Crawford, H.G. Leighton, P. Marsh, G.S. Strong, G.W.K. Moore, H. Ritchie, W.R. Rouse, E.D. Soulis and B. Kochtubajda. 1998. The Mackenzie GEWEX study: the water and energy cycles of a major North American river system. Bull. Amer. Meteor. Soc. 79: 2665-2683.

Walker, A.E., A. Silis, J. Metcalf, M. Davey, R. Brown and B. Goodison. 1999. Snow cover and lake ice determination in the MAGS region using passive microwave satellite and conventional data, p. 89-91. *In* Proc. 4th Scientific Workshop for the Mackenzie GEWEX Study (MAGS), Montreal, Quebec. Natural Sciences and Engineering Research Council of Canada and Environment Canada.

Chapter 13

CLIMATE VARIABILITY AND CHANGE – WETLANDS

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Current Status

Extent and Nature of Canada's Wetlands

The National Wetlands Working Group (NWWG) (1988) defined the term wetland as "land that has the water table at, near, or above the land surface" (National Wetlands Working Group, 1988). Common words for wetlands include swamp, marsh, bog, muskeg, and slough. Typically, wetlands are occupied for the most part by water-loving vegetation such as willows, sedges, cattails, bulrushes and mosses. Where there is open water it is generally less than 2 m deep. In contrast to lakes (see Chapter 12), the open water of wetlands is either very shallow or occupies at most only a small portion of the total area of wetland.

Wetlands occupy 14% of Canada's land surface, about 1,300,000 km^2, an area slightly larger than the entire province of Ontario. The major wetland regions are arctic, sub-arctic, boreal, prairie, temperate, and mountain (Fig. 1). Peatlands, which occur primarily in the boreal and sub-arctic regions, are by far the most common type of wetland, occupying about 1,100,000 km^2, 85% of the total area of wetlands in Canada.

Canadian wetlands can be grouped into five major classes with distinctive properties: bogs, fens, marshes, swamps and shallow water (National Wetlands Working Group, 1997). Bogs receive water from precipitation only and are dominated by sphagnum mosses. Fens receive groundwater as well as precipitation and have sedges as well as mosses and other vegetation. Bogs and fens tend to accumulate peat. Swamps have little standing water, are dominated by trees and shrubs, and may accumulate peat. Marshes have persistent standing water, are rich in emergent aquatic vegetation, but have little moss. Shallow water wetlands have open standing water over much of their area and their vegetation consists mostly of submerged or floating aquatic plants. Most marshes and shallow water wetlands do not form peat.

Wetlands, by their very nature, occur wherever the ground surface is wet or covered with shallow water throughout most of the year. Most Canadian wetlands occur in flat, poorly drained terrain or in depressions in the landscape. Wetlands can also occur on slopes and high land if they are continuously fed by water from rain, melting snow or groundwater seepage. Beavers have created numerous wetlands, especially in the boreal and sub-arctic regions, through their dam-building activities.

For many Canadians the most common acquaintance with wetlands comes about through wetlands within the parks and nature reserves of urbanized areas. These more-or-less artificial marshes and shallow water wetlands commonly also serve as stormwater retention ponds. Relative to other wetland types, the total area of urban wetlands is minute, but their importance is high because they affect the day-to-day lives and recreation of many Canadians.

Values and Functions of Wetlands

Wetlands used to be viewed as unproductive wastelands that can be improved by filling or drainage. That perspective is changing, and wetlands are recognized as having many important functions and values (Government of Canada, 1991). Through storage and slow release of water, wetlands can recharge groundwater, reduce peak flows during floods, and help maintain flow in rivers during dry periods. In regions where they occupy a large proportion of the landscape, such as the Mackenzie River basin, the moist surface of wetlands may also have a moderating influence on climate by maintaining regional evapotranspiration, even during extended dry periods (Rouse et al., 2003).

Wetlands represent critical and highly productive habitat for fish and wildlife and for many unique types of plants. They provide an important resource base for hunting and fishing, and are valued highly for recreational opportunities such as bird watching. The North American Waterfowl Management Plan puts strong emphasis on wetland preservation and habitat enhancement.

Wetlands absorb and store contaminants, such as heavy metals and sulphur from acid rain that enter them via precipitation, surface water flow, and groundwater seepage. Wetlands can also serve an important remediation function because many contaminants such as nitrate are permanently broken down within wetlands.

The important role of Canada's wetlands in the global carbon balance is receiving increased attention. All wetlands store organic carbon, but Canada's peatlands are overwhelmingly important in this respect: they contain about 150 billion tonnes of carbon in the form of peat, 25 times the amount of fossil fuel carbon released each year by the entire world (Roulet, 2000). This peat carbon store has built up over thousands of years and is probably still increasing very slowly, year by year. As long as the peatlands remain saturated to near their surface the carbon will remain in stable storage. Thus, the continued availability of sufficient water to maintain the peatlands is a major concern in the context of climate change. Loss of carbon from the peatlands by fire and decay as a result of increasingly dry conditions would increase emissions of carbon dioxide to the atmosphere, whereas flooding of the peatlands can lead to increased emissions of methane – a potent greenhouse gas. Either way, climatically induced destabilization of Canada's peatlands could have significant repercussions for global climate change.

Vulnerability to Climate Change

Wetlands gain water from precipitation on the wetland itself and from the surrounding uplands by overland runoff, drifting snow, and groundwater inflow. They lose water by evaporation from open water, transpiration from growing plants, surface outflow, and groundwater outflow; hence, the water balance of most wetlands is influenced by the vegetation in the wetland and by land use and vegetation cover on the surrounding uplands.

Due to their large wet area and shallow depths, wetlands are particularly vulnerable to water losses by evapotranspiration. Any variation in climate that increases the relative importance of evaporation compared to precipitation is likely to result in drying out of wetlands. Thus, the shorter warmer winters and longer summers predicted under most climate change scenarios (and that are already occurring in western Canada) imply that wetlands in Canada will be under increasing stress due to water shortage, unless increases in precipitation offset the increased losses by evapotranspiration.

Many Canadian wetlands owe their existence, at least in part, to cold Canadian winters and the resulting permafrost, frozen soil, snow drifting, and river ice jams. Such cold-climate wetlands include those that exist by virtue of impeded drainage due to underlying permafrost, as is the case for many sub-arctic and arctic wetlands (Rouse et al., 1997). In the mountain and arctic regions, small wetlands that depend on meltwater from long-lasting snowbanks are also very sensitive to climatic warming. Millions of small prairie marshes, commonly referred to as potholes or sloughs, owe their existence to snow that blows into them and snowmelt water that flows into them in early spring over the frozen soil of the surrounding land. Some shoreline and delta wetlands owe their existence to inundation by annual or near annual flooding events (e.g., Marsh and Hey, 1994) and will dry out if peak water levels in rivers rise less high due to reduced spring snowmelt freshets or lessening of ice-jam events. All these cold-climate wetlands will be affected by warmer, shorter winters, regardless of how precipitation patterns change.

Some types of wetlands are less likely to be affected by climate change. These include wetlands fed by large deep groundwater systems (cf. Chapter 10) which tend to maintain a steady flow even under large climatic variations (Winter, 2000). Many fens may be in this category if the groundwater flowing in to them constitutes an important part of the total water input. Through-flow wetlands maintained in a balance between large surface water inflows and outflows may be little affected by climate change. Marshes along the margins of lakes and rivers with stable water levels are likely to be insensitive to climate change.

Most peatlands appear to be relatively stable, having persisted and grown for thousands of years, through long wet and dry periods. Recent field studies suggest that the present-day rates of peat growth may be similar to the rates of growth over the past thousand years. However, their future stability under changing climate is uncertain. Bogs are vulnerable to changes in precipitation because that is their only water input. Many peatlands in the sub-arctic region and the northern part of the boreal region are wholly or partly underlain by thin and discontinuous permafrost (Fig. 1), and climate warming will affect these wetlands through thawing and retreat of the permafrost.

Climate warming scenarios suggest the southern boundary of the boreal region may move northwards by hundreds of kilometres over the next century. The reality of this possibility is attested to by the fact that 6000 years ago the southern boundary of the boreal forest and peatlands was located 200 to 400 km north of the present boundary (Vitt et al., 2000). At that time, the climate of northern Canada was warmer than at present because the area received more solar energy due to slow changes in the tilt of the earth's axis. If a large northward movement of the southern limit of the boreal forest does indeed occur, the peatlands may degrade as well and perhaps disappear. The water resources of the area would change drastically and of course there would be very large releases of carbon to the atmosphere.

Present Status

At present there is little region-wide monitoring of wetland status (water levels, area, vegetation, etc.) in the boreal, mountain, sub-arctic and arctic regions, but specific wetlands or wetland complexes are being monitored as part of detailed investigations (Cihlar and Tarnocai, 2000). In the prairie region and the southern margin of the western boreal forest, annual pond counts, carried out in the context of waterfowl management, provide a detailed inventory of wetlands starting in 1955 (Conly and van der Kamp, 2001). It may be surmised that wetlands in the temperate region are closely watched by local agencies, due to their location in densely populated areas.

Boreal and sub-arctic bogs and fens are relatively pristine in terms of human disturbance, although the impacts of clear-cut logging and road construction may be important in the southern boreal forest. In the boreal region, permafrost occurs almost exclusively within the peatlands. The present-day southern distribution of permafrost is in part a relict of the Little Ice Age (approx. 1400–1850) and is not in equilibrium with the present-day climate (Vitt et al., 1999). Through a wide east-west zone of the western boreal region, bordering the southern limit of discontinuous permafrost (Fig. 1), peatlands are affected by warming of the climate over the last 100 years. In this zone, thawing of permafrost causes subsidence of the peat surface and wetter conditions in the peat.

Temperate wetlands (southern Ontario and Quebec, southwest British Columbia) are relatively small in area but lie in the area of main population concentration and are heavily affected by drainage for agriculture and urbanization. Other impacts include peat harvesting for horticulture, changes in water runoff from surrounding areas, changes in vegetation (e.g., cultivation, introduction of purple loosestrife), and changes in wildlife populations (beavers and muskrats).

Shoreline marshes of the Great Lakes are relatively stable but dependent on multi-year wet-dry cycles, which control the water-level changes in the lakes (Mortsch, 1998). Post-glacial uplift, centred on Hudson's Bay, has imposed slow, long-term change of these wetlands through continued tilting of the earth's surface. This glacial isostacy has a controlling influence on the development of the extensive peatlands south and west of Hudson's Bay (Fig. 1).

Delta and floodplain wetlands are primarily dependent on peak water levels in the rivers, caused by extreme flows and ice jams (Marsh and Hey, 1994). Many of these have been affected by changes of flow regime caused by dams and reservoir operations, and change will continue as river beds slowly adjust to the new flow regimes (cf. Chapters 2 and 4).

Prairie wetlands lie in a semi-arid region where potential evaporation exceeds precipitation. They nearly all occur within small closed drainage basins and go through multi-year wet-dry cycles so that the number of wetlands that contain standing water can change by a factor of 10 over a few years (Conly and van der Kamp, 2001). The great majority of these wetlands lie within privately owned cultivated fields, with little regulatory control. Many prairie wetlands have been drained and drainage is continuing, especially along the boreal fringe where water excess is a hindrance to farm operations in most years.

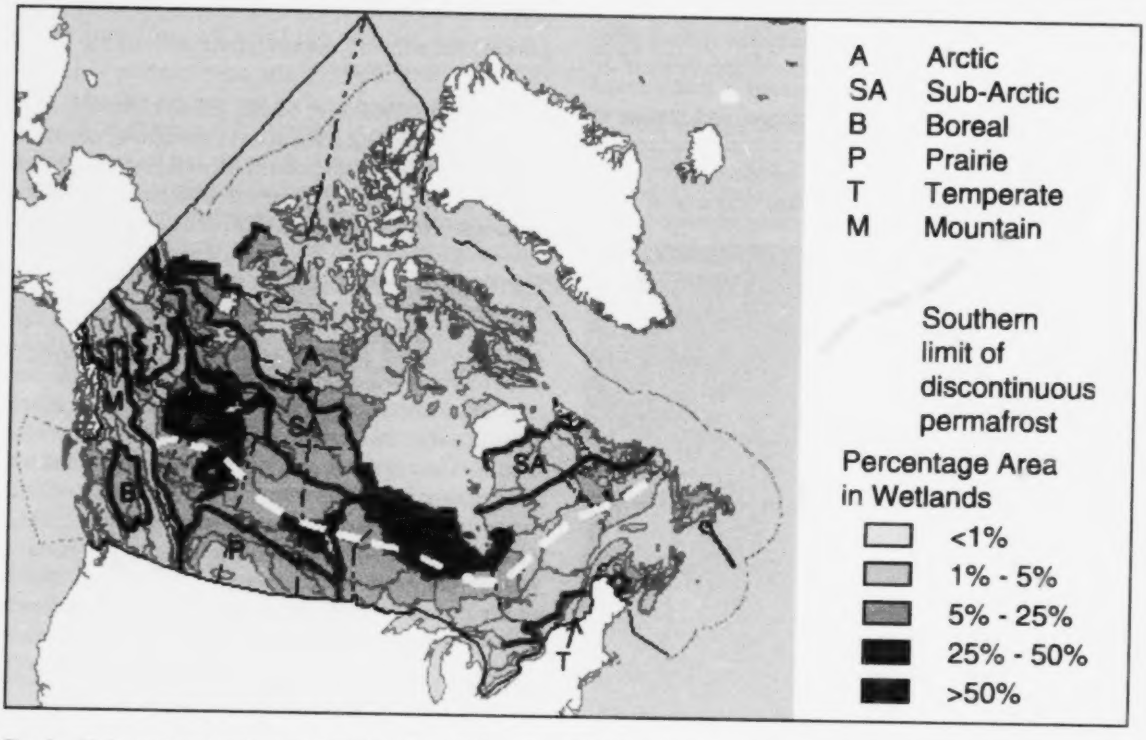

Fig. 1. Major wetland regions of Canada. Boundaries after NWWG (1988). Coloured background represents percentage of area covered by wetlands (National Atlas of Canada, http://atlas.gc.ca).

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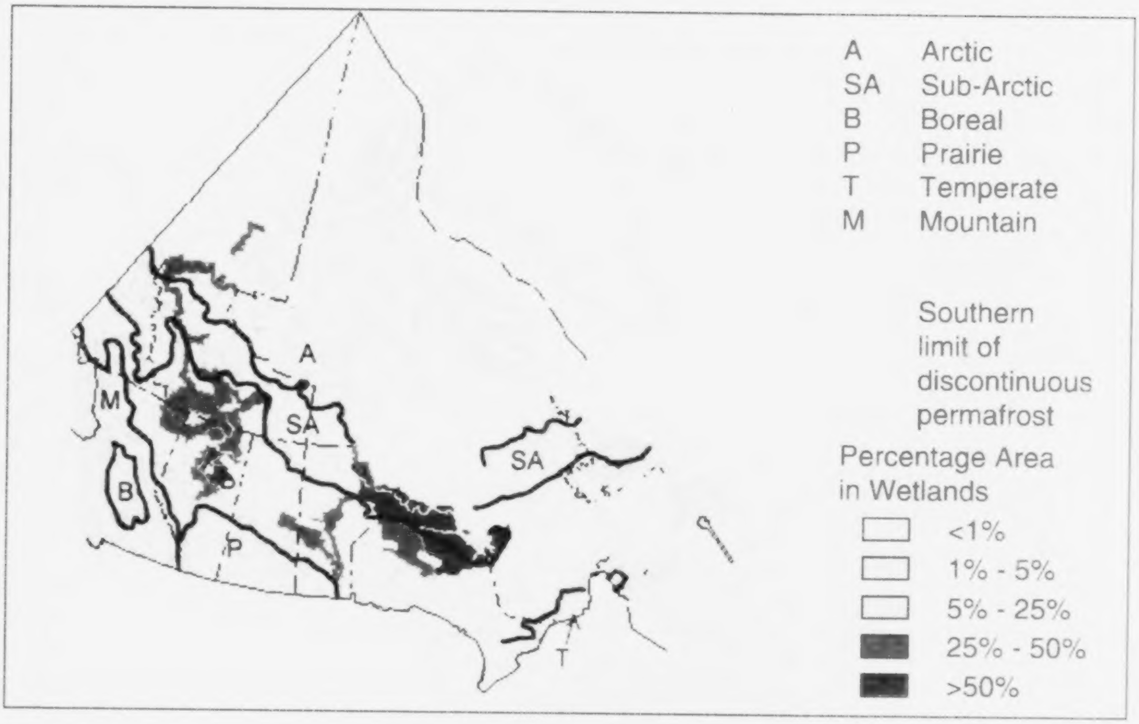

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Trends

In the boreal region of western Canada, permafrost degradation is changing the character of many peatlands. The southern boundary of discontinuous permafrost occurrence has moved northward by tens of kilometres during recent decades and will continue to migrate (Vitt et al., 1999). Extensive peatland plateaus in the northern part of the boreal region, presently underlain by permafrost, will be increasingly affected. The water storage and release characteristics of the peatlands change with thawing of underlying permafrost, and these changes can be expected to affect streamflow and climate feedbacks. The disappearance of permafrost from beneath peatlands can also lead to increased long-term rates of carbon storage in the form of peat because peatlands underlain by permafrost tend to be relatively dry and vulnerable to fire (Robinson and Moore, 2000; Vitt et al., 2000). This retreat of permafrost can be considered the largest present-day impact of climatic change on Canadian wetlands.

In the Arctic and sub-Arctic, longer, warmer summers will lead to a deeper active (thawed) layer in summer, drainage of some wetlands, and creation of others. Areas of ice-rich permafrost, which occur mostly in soft unconsolidated sediments, are especially vulnerable (Beilman et al., 2001).

There do not appear to be any reports of general changes in the southern or northern limits of peatlands over the last few decades, suggesting that if such changes are occurring they are, for now at least, small and not easily detected amidst changes of land use and effects of climatic variability. Drainage and mining of peatlands have reduced the extent of many peatlands in the temperate region and of some peatlands in the southern boreal region. The local impacts of such changes are large, but, in comparison to the total area of peatlands, the impact on a Canada-wide basis is small.

A prairie wetland in the Allan Hills of Saskatchewan.

Prairie wetland numbers and water levels show large year-to-year variations since 1955 when monitoring started (Conly and van der Kamp, 2001). Drainage of wetlands is certainly having a large impact on wetland occurrence in some areas, but overall the percentage of wetlands lost by drainage appears to be in the range of 2 to 4% per decade over the last half century (Watmough et al., 2002). On the surrounding uplands, there has been a marked decline of the area in summer fallow, from 30% in 1985 to 10% in 1999, and a small increase in the proportion of non-cultivated land (Watmough et al., 2002). There are other ongoing gradual and pervasive changes in agricultural practices and land use, such as the current shift to tall stubble and minimum tillage. These changes of land use on the uplands may have a region-wide impact by conserving moisture on the uplands and decreasing runoff to the wetlands (van der Kamp et al., 1999). The effects of climate change will likely continue to be masked by large year-to-year variations of precipitation and runoff, accumulating impacts of wetland drainage, and continuing changes in farming practices and land use.

Delta and floodplain wetlands in southern Canada will become more dependent on peak runoff from summer rainfall and less dependent on spring freshets and ice jams (Prowse and Beltaos, 2002). The corresponding decrease of peak flows, together with longer summertime evaporation periods, will likely lead to drying out of some floodplain wetlands.

Temperate wetlands may be affected by climate change; however, due to their occurrence in the densely populated areas of Canada the main concern with their health will continue to be direct human influences including drainage, urbanization, road salts, and runoff from roads.

Emerging Issues

Impacts of climate change on Canada's boreal and sub-arctic peatlands may be large and carry significant implications for the global atmospheric carbon balance. Similar extensive peatlands exist in northern Russia with a total area twice that of Canada's peatlands (Zhulidov et al., 1997), and it is precisely in these boreal and sub-arctic regions where climatic change will be largest and is already well underway. However, little is as yet known of how Canada's peatlands may react to climate warming or prolonged dry conditions, nor is much known as to whether management of peatlands and of surrounding uplands represents a practical option for maintaining the water balance of the peatlands and protecting the carbon stored in them.

Existing monitoring programs may not detect long-term changes in status of Canadian wetlands due to climate change and other impacts (Cihlar and Tarnocai, 2000). For example, the southern boundary of the boreal wetland region may retreat northwards 200 to 400 km by the year 2050, roughly back to its extent during the warmer climate that prevailed over much of Canada during the early Holocene period (between about 8000 to 5000 years ago). It is highly uncertain whether such a retreat of the boreal wetlands will happen, but if it does indeed occur the resulting loss of peat by burning and by decay would represent a major input of carbon to the earth's atmosphere. The corresponding northward expansion of peatlands would do little to offset the carbon losses in the south, because peat can accumulate only very slowly – at rates of less than one millimetre per year (Vitt et al., 2000). Without adequate data on past and present trends, early detection of gradual but critical changes in the peatlands will not be possible, and evaluation of potential management strategies for maintaining the peatlands will be seriously compromised.

Temporary storage of flood water in wetlands can clearly contribute to moderating floods, at least on a local scale, as demonstrated by the widespread use of stormwater retention ponds in urban areas (Anderson et al., 2002). Wetlands could help reduce floods even in large watersheds, if the total storage capacity of the wetlands is large enough. Such a function of wetlands would also contribute to wildlife habitat, carbon sequestration, erosion control, and water quality improvements. Extensive areas of wetland have been drained for agriculture. Effects of this drainage on peak flows in Canadian rivers and the potential moderating effects of wetland restoration are not well understood and may not be important for extreme flood events (Juliano and Simonovic, 1999). Current hydrological models for wetland water balance and river flow do not incorporate storage and release effects of wetlands very well (Price and Waddington, 2000). Considering the hydrological and ecological benefits of reducing flooding through maintenance and restoration of wetlands on a landscape scale, it is apparent that the role of wetlands in this regard should be taken more seriously and requires more rigorous, multidisciplinary evaluation.

Floodplain, delta and lakeshore wetlands have been affected by changes of river and water-level regime caused by reservoir operations. These wetlands will also be increasingly affected by climate change, notably earlier and smaller spring runoff and increased importance of summertime flood events (Marsh and Lesack, 1996). The nature of these impacts is not well understood at present and possible management options for protecting wetlands are only beginning to be identified.

Prairie wetlands are dependent for their existence on springtime runoff of snowmelt water over frozen cultivated ground. There is an ongoing shift to farming practices that trap snow on the uplands and conserve soil moisture such as tall stubble, minimum tillage, continuous cropping, and conversion to grassland. These are likely having a region-wide impact by decreasing runoff to the wetlands (see Chapter 7). Climate change may also lead to an increased dominance of evaporation over precipitation and runoff. Thus it may be concluded that prairie wetlands are under serious threat. At present there is little information as to the effectiveness of various land management practices for wetland conservation.

Wetlands may be significantly affected by changes in biota due to human interference or to climate change. Changes in beaver populations have had widespread impacts in the past in some areas of Canada. Changes in vegetation such as loss of elms due to Dutch elm disease, or invasion by purple loosestrife may affect the water balance and ecological balance of wetlands. Climate warming is likely to have other impacts on wetland biota: for instance, by reducing the depth and duration of frozen ground or by causing peak water levels and subsequent drying out to occur earlier during the growing season.

Many of the threats to wetlands in Canada have social, economic and environmental aspects. Government policies and regulations with implications for wetlands are sometimes conflicting or inconsistent. There is still a widely held opinion, embedded deep in our culture, that wetlands are "unimproved" land, which should be brought into production for agriculture and forestry or drained and filled for housing and industry. The climate of opinion is changing slowly, but wetlands continue to be inaccessible to public view and to political support.

Knowledge and Program Needs

A nationwide program for wetland monitoring should be set up (Cihlar and Tarnocai, 2000). In addition to direct measurements of water levels, such a program could include remote sensing, air photos, vegetation and wildlife inventories, stable benchmarks for detecting changes of peat thickness, and fixed points for recurrent photos. Resulting data would serve to track changes in the occurrence and status of Canada's wetlands.

In view of the major national and global implications of peatland dynamics under changing climate, there is an urgent need to understand Canada's northern peatlands more fully. The impact of climate change on the southern limit of the boreal wetlands must be better understood. Will the wetlands degrade and retreat? Will they persist and even expand? It depends on a complex interaction among temperature regimes, changes in snowfall and rainfall, water chemistry and vegetation. The role of seasonal freezing and of permafrost in peatland dynamics should be better understood because warming is a clear and ongoing impact of climate change and its effects on peatland are, as yet, poorly understood and predictable.

The lack of adequate wetlands hydrology in hydrological models should be remedied. With reliable and practical models, the impacts of climate change on wetlands can be better predicted, and consequences of wetland dynamics for floods and for low flow can be analyzed and predicted. Such hydrological models would allow evaluation of the potential for using wetlands as a means of moderating floods, and would allow assessment of the potential impacts of climate change on wetland ecology.

Potential impacts of changing farming practices on prairie wetlands should be evaluated so that policies and management practices can be adapted for optimizing the balance between farming and wetland conservation. Similarly, impacts of forestry and other disturbances on boreal wetlands should be better understood so that practices can be adapted to benefit the wetlands.

References

Anderson, B.C., W.E. Watt and J. Marsalek. 2002. Critical issues for stormwater ponds: learning from a decade of research. Water Sci. Technol. 45: 277-283.

Beilman, D.W., D.H. Vitt and L.A. Halsey. 2001. Localized permafrost peatlands in western Canada: definition, distributions and degradation. Arctic, Antarctic Alpine Res. 33: 70-77.

Cihlar, J. and C. Tarnocai (ed.). 2000. Wetlands of Canada and climate change: observation strategy and baseline data. Report of a Workshop, Ottawa, Ont., Jan. 24-25, 2000.

Conly, F.M. and G. van der Kamp. 2001. Monitoring the hydrology of Canadian prairie wetlands to detect the effects of climate change and land use changes. J. Environ. Monit. Assess. 67: 195-215.

Government of Canada. 1991. The federal policy on wetland conservation. Supply and Services Canada. 14 p.

Juliano, K. and S.P. Simonovic. 1999. The impact of wetlands on flood control in the red River Valley of Manitoba. Final Report to the International Joint Commission. Natural Resources Institute, University of Manitoba, Winnipeg, Manitoba. 64 p.

Marsh, P. and M. Hey. 1994. Analysis of spring high water events in the Mackenzie Delta and implications for lake and terrestrial flooding. Geografiska Annaler 4: 221-234.

Marsh, P. and L. Lesack. 1996. The hydrologic regime of perched lakes in the Mackenzie Delta: potential responses to climate change. Limnol. Oceanogr. 41: 849-856.

Mortsch, L. 1998. Assessing the impact of climate change on the Great Lakes shoreline wetlands. Climatic Change 40: 391-416.

National Wetlands Working Group (NWWG). 1997. The Canadian wetland classification system, second edition, B.G. Warner and C.D.A. Rubec (ed.). Wetlands Research Centre, University of Waterloo, Waterloo. 68 p.

National Wetlands Working Group (NWWG). 1988. Wetlands of Canada. Environment Canada and PolyScience Publications. 452 p.

Price, J.S. and J.M. Waddington. 2000. Advances in Canadian wetland hydrology and biogeochemistry. Hydrolog. Process. 14: 1579-1589.

Prowse, T.D. and S. Beltaos. 2002. Climatic control of river-ice hydrology: a review. Hydrolog. Process. 16: 805-822.

Robinson, S.D. and T.R. Moore. 2000. The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada. Arctic, Antarctic Alpine Res. 32: 155-166.

Roulet, N.T. 2000. Peatlands, carbon storage, greenhouse gases, and the Kyoto protocol: prospects and significance for Canada. Wetlands 20: 605-615.

Rouse, W.R., E.M. Blyth, R.W. Crawford, J.R. Gyakum, J.R. Janowicz, B. Kochtubajda, H.G. Leighton, P. Marsh, L. Martz, A. Pietroniro, H. Ritchie, W.M. Schertzer, E.D. Soulis, R.E. Stewart, G.S. Strong and M.K. Woo. 2003. Energy and water cycles in a high-latitude, north-flowing river system. Summary of results from the Mackenzie GEWEX study – Phase 1. Bull. Am. Met. Soc., Jan. 2003, 73-87.

Rouse, W.R., M.S.V. Douglas, R.E. Hecky, A.E. Hershey, G.W. Kling, L. Lesack, P. Marsh, M. Mcdonald, B.J. Nicholson, N.T. Roulet and J.P. Smol. 1997. Effects of climate change on the freshwaters of Arctic and Subarctic North America. Hydrolog. Process. 11: 55-84.

van der Kamp, G., W.J. Stolte and R.G. Clark. 1999. Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass. Hydrolog. Sci. J. 44(3): 387-397.

Vitt, D.H., L.A. Halsey, I.E. Bauer and C. Campbell. 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Can. J. Earth Sci. 37: 683-693.

Vitt, D.H., L.A. Halsey and S.C. Zoltai. 1999. The changing landscape of Canada's western boreal forest: the current dynamics of permafrost. Can. J. Forest Res. 30: 283-287.

Watmough, M.D., D.W. Ingstrup, D.C. Duncan and H.J. Schinke. 2002. Prairie habitat joint venture habitat monitoring program phase 1: recent habitat trends in NAWMP targeted landscapes. Technical Report Series No. 391. Canadian Wildlife Service, Edmonton, Alberta. 93 p.

Winter, T.A. 2000. The vulnerability of wetlands to climate change: a hydrologic landscape perspective. J. Amer. Water Resour. Assoc. 36: 305-311.

Zhulidov, A.V., J.V. Headley, R.D. Robarts, A.M. Nikanorov and A.A. Ischenko. 1997. Atlas of Russian wetlands: biogeography and metal concentrations. Environment Canada. 307 p.

Chapter 14

CLIMATE VARIABILITY AND CHANGE – CRYOSPHERE

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The cryosphere (snow, ice, glaciers and frozen ground/permafrost) is one of the most important components of the Canadian environment. Most of the country experiences several months of snow cover, virtually the entire country experiences seasonally frozen ground, almost half of the terrestrial land surface is underlain by permafrost, most water bodies have a winter ice cover, and glaciers and ice caps constitute the largest volume of land ice in the Northern Hemisphere outside Greenland. The hydrology of most Canadian river basins is dominated by phase changes and seasonal long-term storages involving the cryosphere and cryospheric processes (Woo, 1996).

Cryospheric responses to warming (e.g., an increase in the fraction of precipitation received as rainfall, reduced snow and ice cover duration, disappearance of mountain glaciers, increase in active layer thickness, melting of ground ice) will have important consequences for regional hydrological cycles, particularly in permafrost environments (Woo et al., 1992; Woo, 1996; Rouse et al., 1997). However, quantifying this response and its impact on the hydrological cycle and freshwater supply is a challenge as the cryosphere is characterized by complex linkages and feedbacks, in addition to variable time lags and storages. Current fully coupled global climate models do not incorporate many of the important cryospheric processes for terrestrial areas, or they display important limitations in their ability to simulate key characteristics of cold region climates (Allison et al., 2001). The purpose of this chapter is to assess the current state of understanding of the cryosphere and its role in hydrological systems in Canada, document the cryospheric response to recent warming and implications for freshwater resources, and present a summary of key knowledge gaps and program needs.

Current Status

Precipitation: Hydrological models require accurate information on precipitation amount (adjusted for systematic errors, e.g., Goodison et al., 1998), timing, and type. Winter precipitation, especially snow, is notoriously difficult to measure accurately, and changes in methods of observations, including automation and network reductions, compromise our capacity to define adequately the spatial and temporal variability of winter precipitation across Canada. While some effort has been made to develop gridded precipitation datasets for hydrological studies (e.g., Louie et al., 2002), these are currently only available at monthly time steps. Operational weather forecast models and reanalysis projects have precipitation products at the required spatial and temporal scales, but the accuracy of these datasets is a concern. In addition, large uncertainties in climate model precipitation projections pose similar concerns for investigating cryospheric and hydrological responses to global warming.

Snow Cover: Accurate information on the spatial and temporal evolution of snow cover (extent, depth, snow water equivalent) is required to monitor changes in climate and hydrological systems, as well as for input to a range of operational needs such as drought monitoring, forest fire potential, flood and flow forecasting, and initialization of weather and hydrological models. Canada has extensive *in situ* snow depth and snow course networks, but these are concentrated in southern latitudes and lower elevations, and experienced major contractions during the 1990s (Brown et al., 2000). In spite of these limitations, *in situ* data represent a valuable database for monitoring regional variability and change, and for validating satellite products and climate-weather-hydrology model output.

A variety of satellite datasets is available for mapping snow cover extent and snow water equivalent (SWE). Weekly SWE maps derived from SSM/I passive microwave satellite data are provided in near-real time for the Canadian Prairie Provinces (Goodison and Walker, 1995) at a 25-km resolution. The resolution will increase to 10 km when AMSR-E satellite data become available in 2003. Research to extend this product to other regions of Canada has shown some success (Goïta et al., 2003), but densely forested, mountainous and tundra regions remain challenges.

A range of energy balance models of varying sophistication is available for modelling seasonal snowpack accumulation and ablation, varying from a single layer representation of snow cover (e.g., CLASS - Verseghy, 1991) to multi-layer models that take account of snow grain size evolution (e.g., CROCUS - Brun et al., 1992). Validation studies (e.g., Slater et al., 2001) show that land surface process and snow models are able to capture the broad features of snow cover (duration, depth and SWE) and snowmelt regimes on both an intra- and inter-annual basis for open grass-covered sites. However, modelling the spatial variability of snow cover poses more of a challenge because this requires consideration of blowing snow transport and sublimation, canopy interception and loss, and parameterizations to handle patchy snow conditions. Significant recent advances have been made in understanding these processes at the site scale (Marsh, 1999; Woo et al., 2000). However, further work is needed to incorporate results into land surface process and climate models where surface properties and processes need to be treated at larger spatial scales, e.g., 10-100 km.

Bow Glacier, Canadian Rockies, Alberta.

Interaction of snow and vegetation is important for water resources (Greene et al., 1999). For example, prairie farmers routinely exploit the snow-trapping properties of grain stubble to increase the amount of snow retained on the surface to enhance soil moisture recharge and runoff (Steppuhn, 1981). Forest management practices also influence runoff as outlined in Chapter 8. Recent climate-induced changes to vegetation are modifying water budgets and soil thermal regimes, and it is expected these changes will continue in the future. For example, a transition in vegetation over northern Canada from tundra to shrub-tundra is estimated to generate a deeper, more evenly distributed snow cover, with greater meltwater production (Sturm et al., 2001; Liston et al., 2002). However, the annual change in water supply due to such a vegetation change is more difficult to predict.

Frozen Ground/Permafrost: Frozen ground plays an important role in hydrology through its influence on infiltration, runoff, and groundwater storage and flow. Frozen ground also has indirect influences on hydrology through rooting zone depth (important for vegetation succession and growth) and length of the thaw season (important for evapotranspiration and carbon uptake). In areas with seasonally frozen ground, potential reductions in frost penetration and the duration of soil freezing in response to warming will affect water supply through increased potential for evapotranspiration and changes to the runoff regime. In northern environments, permafrost plays an important role in the water/moisture balance (e.g., control of water table height) as well as the surface energy balance (e.g., delaying the melt runoff process) (Marsh and Woo, 1984).

Large quantities of moisture in permafrost are locked in as ground ice, and thawing will provide additional water. Arctic warming is likely to be associated with an increase in thaw duration and thickness of the surface thaw layer ("active layer") and disappearance of permafrost in some locations (Kane et al., 1991; Anisimov et al., 1997). However, local factors (snow, vegetation, organic layer, proximity to water bodies) add complexity to the ground thermal response (Smith and Riseborough, 1983). Reductions in winter snow depth (observed over much of Canada in the post-1976 period), for example, result in less insulation of the ground layer, which could offset the effect of warmer winter air temperatures.

Extensive ground temperature and active layer monitoring networks in Canada have permitted mapping of ground temperature, permafrost distribution and ground ice conditions (Smith et al., 2001a), and are important data sources for GCM model validations, permafrost sensitivity modelling (Smith and Burgess, 1998) and mapping and impact assessments. Remote sensing also offers capabilities for monitoring the freeze/thaw status of surface soil and changes in surface water area that may be associated with thermokarst development.

The hydrological implications of changes to areas with permafrost are summarized in Woo (1996). These include greater storage capacity for groundwater from a thickened active layer, lowering of the water table, enhanced vertical drainage, and greater potential for evaporation. Differential thaw settlement related to variation in ground ice content can lead to thermokarst topography and exert an influence on distribution of surface water and on drainage patterns. Such changes would modify the runoff regime (e.g., lower spring runoff peak, increased and longer baseflow) and the hydrological behaviour of northern wetlands (e.g., some wetland areas may drain, while some lakes may expand). A study that employed satellite monitoring of thermokarst lakes in the Old Crow Flats area of the Yukon revealed evidence of a drying trend since the early 1970s (Labrecque and Duguay, 2001). In other areas of northwest Canada, lakes in regions with high ground ice content may catastrophically drain (Mackay, 1992; Marsh and Neumann, 2001) due to changes in lake water balance, active layer thickness or slope instability. Potential increases in regional groundwater flow from thawing ground ice may offset the effect of increased evaporation. However, there may be issues of water quality tied to an increased exchange between surface and ground water, as groundwater can have a high dissolved load (Michel and van Everdingen, 1994).

Taliks may develop beneath the active layer if the active layer does not completely freeze back during winter and groundwater may be sustained throughout the winter (Hinzman and Kane, 1992). This could lead to higher winter stream levels, more ice formation, and greater possibility of flooding during breakup (Woo et al., 1992). Slope failures along rivers and streams associated with thaw of ice-rich permafrost would result in increased siltation and may result in damming of rivers and possible upstream flooding (Aylsworth et al., 2000).

Glaciers: The mountain glaciers and icefields in the Cordillera are an important freshwater source (drinking water, irrigation, industrial use, fisheries and hydropower), and there are significant hydrological and ecosystem impacts involved in a reduction or loss of this supply. Runoff from arctic glaciers and ice caps is less important in terms of water supply, but does contribute to sea level rise, and plays a role in near-shore nutrient stratification in the water column and the local sea-ice regime. Hopkinson and Young (1998) determined that glacier wastage in the Bow River at Banff contributed 13% of summer flow in low-flow years, with the contribution exceeding 50% in extreme low-flow years. The glaciers feeding the Bow River have undergone extensive retreat and there is evidence (Moore and Demuth, 2001; Demuth et al., 2002b) that glacier melt contribution is declining. This raises concerns about the sustainability of summer flows in this region of Canada particularly in light of uncertainties in the volume of ice currently stored in glaciers.

Currently, annual mass balance measurements are carried out at five sites in the Cordillera as part of the National Glaciology Program (Demuth, 1996). Monitoring sites are selected to represent major glacier-climate response regions, but there are several important gaps in the network (Cogley and Adams, 1998; Demuth and Koerner, 2001). These historical *in situ* measurements are indispensable (e.g., for validation of models and satellite algorithms), but need to be augmented with remotely sensed information and numerical modelling to assess glacier response to climate variability and change. Recent advances have been made in applying remote sensing to glacier monitoring (Cogley et al., 2001; Copland et al., 2002; Demuth et al., 2002a, submitted for publication), and work has started on generating baseline information on the areal extent of selected glaciers in the Canadian Rockies, Selkirk range and coastal Cordillera of northern B.C. (Sidjak and Wheate, 1999).

Recent advances in glacier-runoff modelling have been made by combining remotely sensed and *in situ* data (Brugman and Pietroniro, 1995; Rott et al., 2000), but the processes take place at scales not yet resolved by most regional or global climate models. Investigating the future response of cordilleran glaciers to climate change will therefore require development of methods for downscaling climate model output to individual ice masses. Moreover, representation of glacier cover within distributed hydrological models requires further development. An improved understanding of glacier hydrology is also needed with respect to glacier hazards. Outburst floods ("jokulhlaup events") from supraglacial, ice marginal and englacial/subglacial sources are a concern in high mountain areas, particularly during periods of rapid glacier wasting. The dynamic component of glacier response to climate change must also be considered, since changing glacier geometry feeds back to the flow regime, which in turn affects the evolution of glacier morphology. Changes in water flux through glaciers may also affect the nature of subglacial drainage systems and runoff response.

Evaporation/Sublimation: The loss of snow mass from sublimation of blowing snow is important in exposed landcover regions such as prairie and tundra. Pomeroy and Gray (1995) estimated sublimation loss over prairie environments to be 15-41% of annual snowfall. They also estimated that approximately one-third of total snowfall falling on spruce and pine was lost through canopy sublimation. More recent modelling work (Dery and Yau, 2001) showed that computed sublimation rates from blowing snow were highly sensitive to assimilation of humidity measurements and evolving thermodynamic fields in the atmospheric boundary layer during blowing snow events. Accurate estimates of sublimation loss at the basin scale are needed to close the water budget. However, there still appear to be major uncertainties in the science of blowing snow sublimation such as the threshold wind speed and particle number density and size distribution near the surface of a layer of blowing snow (Xiao and Taylor, 2002). Detailed observational data are required to address these uncertainties.

As noted in other sections, the cryosphere is an important control of surface evaporation, and reductions in ice and snow cover accompanying warming are likely to be associated with a corresponding increased potential for evaporative losses. This has important implications for lakes (Chapter 12), wetlands (Chapter 13) and agricultural regions.

Freshwater Ice: The duration and thickness of ice cover exert important influences on evaporation, river and lake discharge, ecology, and flooding from ice jams. Potential changes in ice-cover climate (and discharge) will also affect river and on-ice transportation. Recent reviews of the biological and hydrological aspects of river ice were provided by Prowse (2001b,c) and Prowse and Beltaos (2002). The ice-jam process is especially significant in Canada, not only because of the potential for flooding and property damage (Chapter 4), but also because it is an important natural process in cold region river basins that is intimately linked with river ecology (Prowse and Culp, 2003) and the freshwater pulse into the Arctic basin (e.g., Lewis et al., 2000).

Projected warming over Canada is likely to be associated with a reduction in ice cover and an increase in the evaporation season. Ice cover is also implicated in local climate (e.g., lake effect snowfall), which includes the marine cryosphere in the case of Hudson Bay, where sea ice has an important influence on snowfall accumulation over one of the main hydroelectricity producing regions of Quebec. Ice formation and decay are sensitive to changes in climatic conditions, and Beltaos and Prowse (2001) found that increased incidence of mid-winter melt and associated breakup events in some temperate regions of Canada could actually enhance the frequency and severity of ice jams.

A variety of *in situ* observations for lake and river ice has been collected in Canada (see summary in Brown et al., 2002). In general, the *in situ* databases are characterized by relatively short periods of record (little data prior to 1950) with major contractions in networks during the 1990s. Canada's *in situ* networks are no longer adequate to provide the primary information desired for lake ice monitoring. Remote sensing offers a viable alternative observing strategy, but the satellite data record is still too short for documenting variability and change. This situation requires the development of approaches to merge available *in situ* and satellite observations to create a consistent, long-term time series of lake ice freeze-up/breakup and ice cover processes. River ice is more difficult to monitor routinely, but high-resolution SAR data have been used successfully in experimental trials (Pietroniro and Leconte, 2000).

Considerable progress has been made in our ability to model formation and decay of lake ice, and one-dimensional thermodynamic lake ice models (e.g., Ménard et al., 2002) have been able to reproduce observed variability in lake ice cover using local meteorological forcing data. Similar progress has been made in modelling the hydraulic effects of ice cover on river discharge (Hicks and Healy, 2003) and the ice-jamming process (Beltaos, 1995). Modification of the ice-jam flood process through flow regulation has also been suggested and field tested as an adaptation strategy for dealing with the drying effects of climate change (Prowse 2001a; Prowse et al., 2002b).

Cryospheric Response to Recent Climate Warming

Glaciers: There is widespread evidence of a major retreat of small alpine and continental glaciers in response to twentieth century warming (Dyurgerov and Meier, 1997; Cogley and Adams, 1998). Demuth and Keller (2002) documented recent acceleration of glacier contraction in Canada's southern Cordillera consistent with global trends, and Demuth et al. (2002b) documented a dramatic contraction of outlet glaciers and glacier cover over the eastern slopes of the Rocky Mountains since the Neo-glacial maximum stage (ca. 1850). These decreases in the areal extent of glacier ice cover during the twentieth century have been accompanied by corresponding decreases in the contribution to downstream summer flow volumes to the western Prairies, which exacerbate the impact of drought conditions in this region of Canada because less water is available from irrigation reservoirs on major rivers.

It has been suggested that a temporary period of enhanced flow from glacier sources may be established when large areas of upland ice (e.g., Columbia Icefield) are subject to persistent melting conditions (Demuth et al., 2002c). However, forecasting the timing, duration and magnitude of this enhanced glacier contribution to runoff is complicated by uncertainties in how temperature and precipitation regimes may change at higher elevations, as well as by the dynamic component of glacier response There is also the possibility of major shifts in drainage divides and even in the basins to which glacierized areas contribute runoff when major icefields are melting.

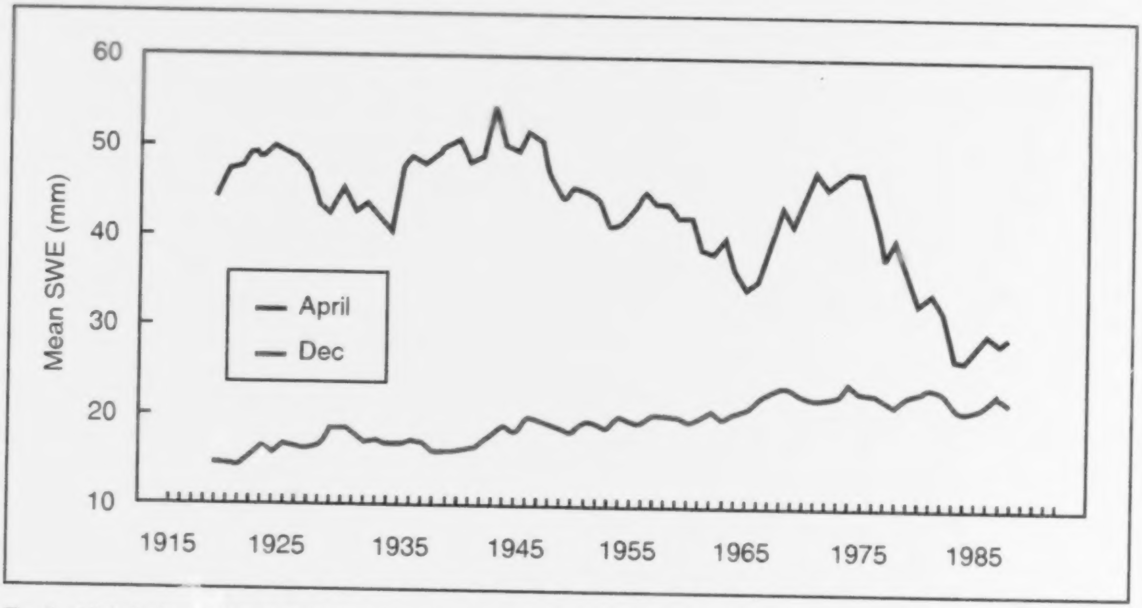


Fig. 1. Historical variation in estimated snow water equivalent (SWE) for December and April over the mid-latitude region of North America. Source: Brown (2000).

Glacier mass balance over the Cordillera is also strongly influenced by variations in atmospheric circulation, notably the Pacific Decadal Oscillation (PDO) and Pacific-North America (PNA) patterns (Moore and Demuth, 2001; Demuth and Keller, 2002). Documenting the sensitivity of glaciers to these modes of atmospheric variability is important since this response will be superimposed on greenhouse gas-induced climate changes, and because certain modes of atmospheric variability may be more persistent under a warmer climate (IPCC, 2001).

Snow Cover (SWE, depth, extent): Analysis of *in situ* snow depth data showed the post-1970s period was characterized by significant reductions in winter snow depth and spring snow cover (earlier melt) over much of the country and in western Canada in particular (Brown and Braaten, 1998). This finding was confirmed by satellite data from the early 1970s that showed extensive reductions in spring season snow cover over western Canada and the Arctic. The satellite data show little change in snow cover at the start of the snow season, although *in situ* data from the early 2000s are starting to show evidence of a delay to the start of the snow season. Brown (2000) reported somewhat similar contrasting trends in estimated SWE over mid-latitudes of North America, with winter showing significant increases in SWE over the 1915-1992 period in response to increasing precipitation, and spring showing a significant decrease over the same period (Fig. 1). The contrasting seasonal response is consistent with the observations of Groisman et al. (1994) that snow cover exerts the strongest feedback to the earth radiation balance in the spring period.

The response of mountain snowpacks to a changing climate is a major concern over western Canada where snowmelt runoff is a key component in reservoir recharge. Moore and McKendry (1996) showed that snowpack conditions in southern British Columbia were dominated by atmospheric circulation patterns linked to decadal-scale shifts in sea surface temperatures. They also found evidence of an abrupt shift to less winter snow accumulation after 1976, which coincided with a well-documented shift in the Pacific-North America (PNA) teleconnection pattern to more positive values (Leathers and Palecki, 1992). This shift has been associated with reduced snow cover, earlier runoff, and more negative glacier mass balances over much of western North America. Brown (1998) showed that ENSO was responsible for significant anomalies in regional snow cover over western Canada with El Niño associated with below-average winter snow cover extent, and La Niña with above-average SWE. Abrupt shifts in atmospheric circulation such as the 1976 change in the PNA pattern and a recent tendency toward more frequent El Niño events add an additional level of uncertainty onto the regional snow cover response to global climate warming.

Freshwater Ice: Magnuson et al. (2000) documented a hemispheric-wide trend toward earlier breakup of river ice consistent with a widespread cryospheric response to twentieth century warming (IPCC, 2001). Within Canada, the available river and lake freeze-up/breakup data suggest there is more regional complexity to this trend. Zhang et al. (2001) analyzed a 249-station subset of data from the Reference Hydrometric Basin Network to infer information on river freeze-up/breakup trends across Canada over the 1947-1996 period. Results showed an interesting regional difference with rivers over western Canada generally showing trends toward earlier breakup, and rivers over the Maritimes showing later breakup. The patterns have been linked to changes in seasonal warming (0°C-isotherm) and specific atmospheric circulation patterns (Bonsal and Prowse, 2003; Bonsal et al., 2001; Prowse et al., 2002a). Marsh et al. (2002) documented a similar trend towards earlier breakup of the Mackenzie River near its mouth, but did not find a trend in the magnitude of breakup. Further evidence of important regional differences in lake ice freeze-up and breakup trends were provided by Duguay et al. (2002).

Frozen Ground/Permafrost: Young and Woo (2002) argued that it is very difficult to separate the freeze-thaw response of frozen ground to interdecadal climate variability and climatic trend. Recent analyses (IPCC, 2001) revealed that permafrost in many regions of the earth is warming; however, monitoring of shallow permafrost only began in earnest over the last few decades. In Canada, the onset, magnitude, and rate of warming was shown to vary regionally due to different regional climates and effects of snow cover and surface layer properties. For example, the Mackenzie Delta and High Arctic regions showed evidence of recent permafrost warming (Romanovsky et al., 2002), while parts of northeastern and northwestern Canada showed evidence of recent permafrost cooling (Allard et al., 1995; Burn, 1998). There is also evidence of increased thaw depths in the Mackenzie Delta. Large increases were associated with the extreme warming encountered during the summer of 1998. At sites with ice-rich soil, the increase in thaw penetration was accompanied by significant ground subsidence and, hence, very little change in active layer thickness (Smith et al., 2001b; Wolfe et al., 2000). Recent evidence of permafrost melting in the northern Prairie Provinces was reported by Beilman et al. (2001).

Knowledge and Program Needs

Data/Monitoring Needs

- Gridded, high-resolution (~10 km) spatially representative precipitation data at a 6-hourly interval (or better) are needed for running climate and hydrological models. Observed precipitation datasets should be corrected for systematic errors and a concerted effort made to understand the impact of automation (e.g., through intercomparisons of manual and auto-gauge measurements under operational conditions).
- Reliable cryospheric datasets of variables such as SWE and ice cover are needed for documenting variability and change, and for model input and validation. This requires the combination of *in situ*, satellite and model-derived information, as well as application of data assimilation methods. Accurate datasets covering a range of spatial scales are urgently needed for development and validation of scaling approaches.
- A systematic approach should be implemented to determine the amount of water stored in cordilleran glaciers and the rate at which it is melting. This will require satellite monitoring of areal extent for decadal reassessments of glacier area, development of upscaling/downscaling methods to perform regional mass balance simulations (validated with field or remote sensing data), and systematic (approximately 5-year interval) airborne laser altimetry surveying to detect elevation changes. Digitizing of historical data at the Canadian Glacier Inventory is needed to document glacier response to climate over the past 40-50 years (Munro, 2000).
- Basic research is required to understand the interrelationships and feedbacks between cryospheric and hydrological systems and provide reliable estimates of changes in water yields in response to a changing climate. The WCRP Climate and Cryosphere (CliC) project implementation plan proposed development of field campaigns at a number of "Super Sites" to improve knowledge of cold climate processes and interactions and to develop parameterizations of important cryospheric processes: for example, sublimation, snow-vegetation interactions, and the role of frozen ground in infiltration and drainage for coupled climate-hydrological models. The "Super Site" concept can also be used to validate remotely sensed products, evaluate measurement systems, and investigate scaling issues.

Modelling Needs

- Controlled intercomparisons of coupled climate-hydrological models with high quality Canadian basin-scale datasets are needed. This entails a major effort to develop the required surface property and model forcing fields.
- We need a better understanding of the role increased regional groundwater flow from ground ice melt may have in the water balance, as well as in determining the future permafrost distribution under climate warming. In addition, an improved understanding of the development of more coherent drainage systems in peatlands/wetlands in response to thawing is required. This is important in identifying water routing pathways and for future carbon sources and sinks (Chapter 13).
- New knowledge of cryospheric processes such as frozen soil infiltration should be incorporated into Canadian coupled climate-hydrological models (Woo et al., 2000).
- Regional climate and hydrological model runs for current and future climate conditions are required for testing our ability to model the northern cryosphere and for considering future changes (e.g., Mackenzie GEWEX Study - MAGS).

- Determining the future response of glaciers to climate change requires new approaches and methods for generating realistic future climates in mountainous regions (e.g., statistical downscaling and nested regional climate models). It also requires a new type of glacier model that includes the higher order stress terms important for flow over complex topography, but at the same time can be run at a regional scale.

Other Issues

- Canada is losing its field expertise in cryospheric and hydrological science. Improved field training and incentives for young scientists to work in snow and ice are urgently needed.
- Dwindling logistical support for northern research activities is having a debilitating impact on Canada's capacity to carry out fundamental scientific research on northern climate and hydrological systems. This situation contributes to the loss of field expertise described above.

Acknowledgements

The authors are very grateful for the valuable review comments provided by external reviewers Wayne Rouse (McMaster University), Martin Sharp (University of Alberta), and Fred Wrona (NWRI).

References

Allard, M., B.L. Wang and J.A. Pilon. 1995. Recent cooling along the southern shore of Hudson Strait, Quebec, Canada, documented from permafrost temperature measurements. Arctic Alpine Res. 27: 157-166.

Allison, I., R.G. Barry and B.E. Goodison (ed.). 2001. Climate and Cryosphere (CliC) project science and co-ordination plan, Version 1, January 2001, WCRP-114, WMO/TD No. 1053. 96 p.

Anisimov O.A., N.I. Shiklomanov and F.E. Nelson. 1997. Global warming and active-layer thickness: results from transient general circulation models. Global and Planetary Change 15: 61-78.

Aylsworth, J.M., A. Duk-Rodkin, T. Robertson and J.A. Traynor. 2000. Landslides of the Mackenzie valley and adjacent mountainous and coastal regions, p. 167-176. *In* L.D. Dyke and G.R. Brooks (ed.), The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change. Geological Survey of Canada, Bulletin 547.

Beilman, D.W., D.H. Vitt and L.A. Halsey. 2001. Localized permafrost peatlands in western Canada: definition, distributions, and degradation. Arctic, Antarctic and Alpine Research 33: 70-77.

Beltaos, S. (ed.). 1995. River ice jams. Water Resources Publications, Highlands Ranch, Co., U.S.A.

Beltaos, S. and T.D. Prowse. 2001. Climate impacts on extreme ice-jam events in Canadian rivers. Hydrolog. Sci. J. 46: 157-181.

Bonsal, B.R. and T.D. Prowse. 2003. Trends and variability in spring and autumn 0°C-isotherm dates over Canada. Climatic Change, In press.

Bonsal, B.R., T.D. Prowse and M.P. Lacroix. 2001. Linkages between spring 0°C isotherm dates and hydrocryospheric variables over Arctic Canada, p. 75. In Proceedings, International Symposium on Arctic Feedbacks to Global Change, October 25-27, 2001, Rovaniemi, Finland.

Brown, R.D. 1998. El Niño and North American snow cover, p. 165-172. *In* Proc. 55th Eastern Snow Conference, Jackson, N.H., June 4-6, 1998.

Brown, R.D. 2000. Northern Hemisphere snow cover variability and change, 1915-1997. J. Climate 13: 2339-2355.

Brown, R.D. and R.O. Braaten. 1998. Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. Atmos.-Ocean 36: 37-45.

Brown, R.D., C.R. Duguay, B.E. Goodison, T.D. Prowse, B. Ramsay and A.E. Walker. 2002. Freshwater ice monitoring in Canada - an assessment of Canadian contributions for global climate monitoring, p. 368-376. *In* Proc. 16th IAHR International Symposium on Ice, Dunedin, New Zealand, December 2-6, 2002, Vol. 1.

Brown, R.D., A. Walker and B.E. Goodison. 2000. Seasonal snow cover monitoring in Canada - an assessment of Canadian contributions for global climate monitoring, p. 131-141. *In* Proc. 57th Eastern Snow Conference, Syracuse, N.Y., May 17-19, 2000.

Brugman, M.M. and A. Pietroniro. 1995. Application of SAR and LANDSAT to modelling glacier runoff: preliminary results from the Illecillewaet Glacier test basin, p. 241-257. *In* Applications of remote sensing in hydrology, Proceedings of the 2nd International Workshop, National Hydrology Research Institute Symposium 14.

Burn, C.R. 1998. Field investigations of permafrost and climatic change in northwest North America, p. 107-120. *In* A.G. Lewkowicz and M. Allard (ed.), Permafrost Seventh International Conference Proceedings, Collection Nordicana No. 57.

Brun, E., P. David, M. Sudul and G. Brunot. 1992. A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting. J. Glaciol. 38: 13-22.

Cogley, J.G. and W.P. Adams. 1998. Mass balance of glaciers other than the ice sheets. J. Glaciology 44: 315-325.

Cogley, J.G., M.A. Ecclestone and D.T. Anderson. 2001. Melting on glaciers: environmental controls examined with orbital radar. Hydrolog. Process. 15: 3541-3558.

Copland, L., M. Sharp and J. Dowdeswell. 2002. The distribution and flow characteristics of surge-type glaciers in the Canadian High Arctic. Annals of Glaciology 36: 73-81.

Demuth, M.N. 1996. The Canadian glacier variations monitoring and assessment network: status and future perspectives, p. 37-51. *In* R.S. Williams, Jr. and J.G. Ferrigno (ed.), Proceedings of the Workshop on Long-term Monitoring of Glacier Fluctuations in North America and Northwestern Europe, Tacoma, U.S.A., September 11-13, 1996. United States Geological Survey 98-31 Open-File Report.

Demuth, M.N., C. Hopkinson, M. Sitar, A. Pietroniro and L. Chasmer. 2002a. Airborne scanning LASER terrain mapping of Peyto Glacier, Wapta and Waputik Icefields, Canada: first results and future prospects. Geological Survey of Canada Open File.

Demuth, M.N. and R. Keller. 2002. An assessment of the mass balance of Peyto Glacier (1966-1995) and its relation to recent and past-century climatic variability, p. 83-132. *In* M.N. Demuth, D.S. Munro and G.J. Young (ed.), Peyto Glacier: one century of science. National Hydrology Research Institute Science Report #8.

Demuth, M. and R. Koerner. 2001. Canadian glacier/ice cap-climate observing system: current status and future perspectives. Summary Report of the Glacier/Ice Cap Working Group, GCOS Monitoring Networks Workshop, Ottawa, Canada, 2000-January 28-29, National Glaciology Program, Geological Survey of Canada, Ottawa, Ont.

Demuth, M.N., A. Pietroniro and T.B.M.J. Ouarda. 2002b. Streamflow regime shifts resulting from recent glacier fluctuations in the eastern slopes of the Canadian Rocky Mountains, p. 35. Abstract Proceedings, Canadian Water Resources Association Annual Conference, Winnipeg, Canada.

Demuth, M.N., A. Pietroniro, T. Ouarda and J. Yetter. 2002c. The impact of climate change on the glaciers of the Canadian Rocky Mountain eastern slopes and implications for water resource adaptation in the Canadian prairies - Phase I. Geological Survey of Canada Open File 4322.

Dery, S.J. and M.K. Yau. 2001. Simulation of blowing snow in the Canadian Arctic using a double-moment model. Boundary-Layer Meteorology 99: 297-316.

Duguay, C.R., F. Lenormand, R.D. Brown and T.D. Prowse. 2002. Historical trends in lake ice cover in northern Canada. *In* Proc. 16th IAHR International Symposium on Ice, Dunedin, New Zealand, December 2-6, 2002.

Dyurgerov, M. and M. Meier. 1997. Mass balance of mountain and sub-polar glaciers: a new global assessment for 1961-1990. Arctic Alpine Res. 29: 392-401.

Goïta, K., A.E. Walker and B.E. Goodison. 2003. Algorithm development for the estimation of snow water equivalent in the boreal forest using passive microwave data. Int. J. Remote Sensing 24: 1097-1102.

Goodison, B.E., P.Y.T. Louie and D. Yang. 1998. WMO solid precipitation measurement intercomparison. WMO Instruments and Observing Methods Report No. 67, WMO/TD No. 872.

Goodison, B.E. and A.E. Walker. 1995. Canadian development and use of snow cover information from passive microwave satellite data, p. 245-262. *In* Passive Microwave Remote Sensing of Land-Atmosphere Interactions, Utrecht, The Netherlands.

Greene, E.M., G.E. Liston and R.A. Pielke. 1999. Relationships between landscape, snowcover depletion, and regional weather and climate. Hydrolog. Process. 13: 2453-2466.

Groisman, P.Ya., T.R. Karl and R.W. Knight. 1994. Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. Science 263: 198-200.

Hicks, F. and D. Healy. 2003. Determining winter discharge by hydraulic modeling. Can. J. Civil Eng. 30: 101-112.

Hinzman, L.D. and D.L. Kane. 1992. Potential response of an arctic watershed during a period of global warming. J. Geophys. Res. 97(D3): 2811-2820.

Hopkinson, C. and G.J. Young. 1998. The effect of glacier wastage on the flow of the Bow River at Banff, Alberta, 1951-1993. Hydrolog. Process. 12: 1745-1763.

IPCC. 2001. Climate change 2001 - the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden and D. Xiaosu (ed.). Cambridge University Press, UK. 944 p.

Kane, D.L., L.D. Hinzman and J.P. Zarling. 1991. Thermal response of the active layer to climatic warming in a permafrost environment. Cold Regions Sci. Technol. 19: 111-122.

Labrecque, S. and C.R. Duguay. 2001. Étude de la dynamique spatio-temporelle récente des lacs thermokarstiques de la plaine Old Crow Flats, Yukon, par télédétection, p. 585-590. *In* Proc. 23rd Canadian Symp. on Remote Sensing - 10e Congrès de l'Association québécoise de télédétection.

Leathers, D.J. and M.A. Palecki. 1992. The Pacific/North American teleconnection pattern and United States climate. Part II: temporal characteristics and index specification. J. Climate 5: 707-716.

Lewis, E.L., E.P. Jones, P. Lemke, T.D. Prowse and P. Wadhams (ed.). 2000. The freshwater budget of the Arctic Ocean. Kluwer Academic Publishers, Dordrecht. 623 p.

Liston, G.E., J.P. McFadden, M. Sturm and R.A. Pielke. 2002. Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs. Global Change Biol. 8: 17-32.

Louie, P.Y.T., W.D. Hogg, M.D. MacKay, X. Zhang and R.F. Hopkinson. 2002. The water balance climatology of the Mackenzie basin with reference to the 1994/95 water year. Atmos.-Ocean 40: 159-180.

Mackay, J.R. 1992. Lake stability in an ice-rich permafrost environment: examples from the western Arctic coast, p. 1-26. *In* R.D. Robarts and M.L. Bothwell (ed.), Aquatic ecosystems in semi-arid regions: implications for resource management. NHRI Symposium Series 7, Environment Canada, Saskatoon, Saskatchewan.

Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart and V.S. Vuglinski. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289: 1743-1746.

Marsh, P. 1999. Snowcover formation and melt: recent advances and future prospects. Hydrolog. Process. 13: 2519-2536.

Marsh, P. and N. Neumann. 2001. Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada. Hydrolog. Process. 15: 3433-3446.

Marsh, P., C. Onclin and N. Neumann. 2002. Water and energy fluxes in the lower Mackenzie Valley, 1994/95. Atmos.-Ocean 40: 245-256.

Marsh, P. and M. Woo. 1984. Wetting front advance and freezing of meltwater within a snow cover. 1. Observations in the Canadian Arctic. Water Resour. Res. 20: 1853-1864.

Ménard, P., C.R. Duguay, G.M. Flato and W.R. Rouse. 2002. Simulation of ice phenology on Great Slave Lake, Northwest Territories, Canada. Hydrolog. Process. 16: 3691-3706.

Michel, F.A. and R.O. van Everdingen. 1994. Changes in hydrogeologic regimes in permafrost regions due to climatic change. Permafrost and Periglacial Processes 5: 191-195.

Moore, R.D. and M.N. Demuth. 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrolog. Process. 15: 3473-3486.

Moore, R.D. and I.G. McKendry. 1996. Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. Water Resour. Res. 32: 623-632.

Munro, D.S. 2000. Progress in glacier hydrology: a Canadian perspective. Hydrolog. Process. 14: 1627-1640.

Pietroniro, A. and R. Leconte. 2000. A review of Canadian remote sensing applications in hydrology, 1995-1999. Hydrolog. Process. 14: 1641-1666.

Pomeroy, J.W. and D.M. Gray. 1995. Snowcover - accumulation, relocation and management. National Hydrology Research Institute Science Report No. 7, Saskatoon, Canada. 144 p.

Prowse, T.D. 2001a. An adaptation strategy for mitigating the combined effects of climate variability and flow regulation on a major river delta. European Geophysical Society, 26th General Assembly, Geophysical Research Abstracts, Vol. 3.

Prowse, T.D. 2001b. River-ice ecology: I: hydrologic, geomorphic and water-quality aspects. J. Cold Regions Eng. 15: 1-16.

Prowse, T.D. 2001c. River ice ecology. II: biological aspect. J. Cold Regions Eng. 15: 17-33.

Prowse, T.D. and S. Beltaos. 2002. Climatic control of river-ice hydrology: a review. Hydrolog. Process. 16: 805-822.

Prowse, T.D., B.R. Bonsal, M.P. Lacroix and S. Beltaos. 2002a. River-ice breakup in northern Canada: trends and atmospheric linkages. *In* Proc. 16th IAHR International Symposium on Ice, Dunedin, New Zealand, December 2-6, 2002, In press.

Prowse, T.D. and J.M. Culp. 2003. Ice breakup: a neglected factor in river ecology. Can. J. Civil Eng. 30: 128-144.

Prowse, T.D., D. Peters, S. Beltaos, A. Pietroniro, L. Romolo, J. Töyrä and R. Leconte. 2002b. Restoring ice-jam floodwater to a drying delta ecosystem. Water Int. 27: 58-69.

Romanovsky, V., M. Burgess, S. Smith, K. Yoshikawa and J. Brown. 2002. Permafrost temperature records: indicators of climate change. EOS, Transactions American Geophysical Union 83(589): 593-594.

Rott, H. et al. 2000. Hydrology of alpine and high latitude basins, final report. Mitteilung Nr. 4 Institute for Meteorology and Geophysics, University of Innsbruck. 201 p.

Rouse, W.R., M. Douglas, R. Hecky, G. Kling, L. Lesack, P. Marsh, M. MacDonald, B. Nicholson, N. Roulet and J. Smol. 1997. Effects of climate change on freshwaters of arctic and subarctic North America. Hydrolog. Process. 11: 873-902.

Sidjak, R.W. and R.D. Wheate. 1999. Glacier mapping of the Illecillewaet Icefield, British Columbia, Canada, using Landsat TM and digital elevation data. Int. J. Remote Sensing 20: 273-284.

Slater, A.G. et al. 2001. The representation of snow in land surface schemes: results from PILPS 2(D). J. Hydrometeorology 2: 7-25.

Smith, S.L. and M.M. Burgess. 1998. Mapping the response of permafrost in Canada to climate warming, p. 163-171. *In* Current research 1998-E, Geological Survey of Canada.

Smith, S.L., M.M. Burgess and J.A. Heginbottom. 2001a. Permafrost in Canada, a challenge to northern development, p. 241-264. *In* G.R. Brooks (ed.), A synthesis of geological hazards in Canada. Geological Survey of Canada, Bulletin 548.

Smith, S.L., M.M. Burgess and F.M. Nixon. 2001b. Response of active-layer and permafrost temperatures to warming during 1998 in the Mackenzie Delta, Northwest Territories and at Canadian Forces Station Alert and Baker Lake, Nunavut. Geological Survey of Canada, Current Research 2001-E5. 8 p.

Smith, M.W. and D.W. Riseborough. 1983. Permafrost sensitivity of climatic change, Vol. 1, p. 1178-1183. *In* Proceedings of 4th International Conference on Permafrost, Fairbanks, Alaska, National Academy Press, Washington, DC.

Steppuhn, H. 1981. Snow and agriculture, p. 60-126. *In* D.M. Gray and D.H. Male (ed.), Handbook of snow, principles, processes, management and use. Pergamon, Toronto.

Sturm, M., J.P. McFadden, G.E. Liston, F.S. Chapin, C.H. Racine and J. Holmgren. 2001. Snow-shrub interactions in Arctic tundra: a hypothesis with climatic implications. J. Climate 14: 336-344.

Verseghy, D. 1991. CLASS - a Canadian land surface scheme for GCMs. I: soil model. Int. J. Climatol. 11: 111-133.

Wolfe, S.A., E. Kotler and F.M. Nixon. 2000. Recent warming impacts in the Mackenzie Delta, Northwest Territories, and northern Yukon Territory coastal areas, Vol. 9, p. 53. *In* Geological Survey of Canada, Current Research 52 2000-B1.

Woo, M.-k. 1996. Hydrology of northern North America under global warming, p. 73-86. *In* J.A.A. Jones, C. Liu, M.-k. Woo and H.-t. Kung (ed.), Regional hydrological response to climate change. Kluwer Academic Publishers.

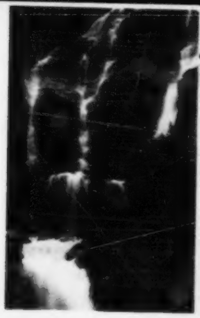
Woo, M.-k., A.G. Lewkowicz and W.R. Rouse. 1992. Response of the Canadian permafrost environment to climatic change. Phys. Geog. 13: 287-317.

Woo, M.-k., P. Marsh and J.W. Pomeroy. 2000. Snow, frozen soils and permafrost hydrology in Canada, 1995-1998. Hydrolog. Process. 14: 1591-1611.

Young, K.L. and M.K. Woo. 2002. Thermo-hydrological responses to an exceptionally warm, dry summer in a High Arctic environment. Nordic Hydrology, In press.

Xiao, J.B. and P.A. Taylor. 2002. On equilibrium profiles of suspended particles. Boundary-Layer Meteorology 105: 471-482.

Zhang, X., K.D. Harvey, W.D. Hogg and T.R. Yuzyk. 2001. Trends in Canadian streamflow. Water Resour. Res. 37: 987-998.



Chapter 15

INTEGRATED AND CUMULATIVE THREATS TO WATER AVAILABILITY

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Introduction

The institutions that have guided development of Canada's water resources have been varied and have evolved in response to different and changing human and biophysical circumstances. Canadians have sought ways to promote development through providing additional storage of water, reducing variability of river flows, and redirecting and utilizing groundwater flows. Only recently have there been concerted efforts to reduce the demand for water. Harnessing water resources has often led to unintended impacts and problems, some of which are described in earlier chapters. Since water is connected through the hydrologic cycle, it is sometimes difficult to manage one water use without significantly affecting another. Many water resource problems can be termed "wicked" or "meta-problems" because they extend beyond the scope of a single government agency and level of government, and are associated with high levels of change, complexity, uncertainty and conflict (Mitchell, 2002). Differences of opinion over the goals to be achieved, and uncertainty and disagreement about the means to solve meta-problems are common. Problems can be chronic or acute, and may be bound or framed in technical, economic, legal, political and social ways. Proposed solutions will be multifaceted; hence information concerning human use and biophysical aspects of water and related resources will be required if decision making is to be adequately informed.

Integrated and cumulative threats to water supply are types of meta-problems. *Integrated threats* to the water supply are threats that emerge when combinations of stresses occur (e.g., conjunctive groundwater and surface water problems, expected changes in climate and population with associated changes in water demand, simultaneous changes in water uses, etc.). *Cumulative threats* refer to evolving impacts over time. These emerge slowly and evolve over long periods. The process of attempting to solve these kinds of problems will commonly involve participation of various agencies, possibly from all levels of government, the private sector, users/clients, relevant non-government organizations, and the general public. Furthermore, the problem-solving process may itself evolve over time rather than being predetermined at the outset. Climate change is a good example of a potential cumulative threat.

Previous chapters have dealt with some specific aspects of these meta-problems and have highlighted various uncertainties, complexities, conflicts and changes associated with water quantity challenges. Rather than reviewing all aspects of the problem, this chapter turns its attention to two elements:

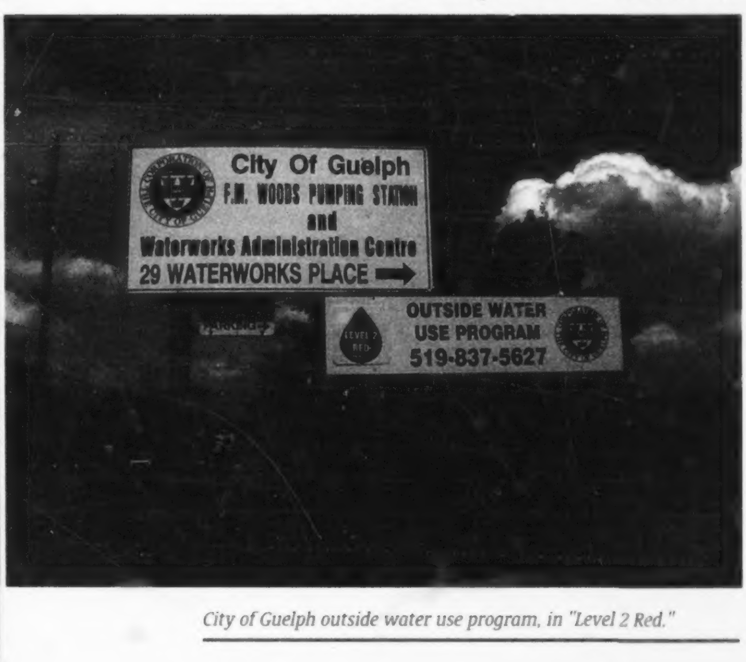
1. A description of how integrated and cumulative threats to water supply can develop. The case of the Columbia basin illustrates the ways in which decisions made by government agencies with relatively narrow mandates and acting independently from one another contributed to the escalation and creation of a meta-problem.
2. Illustrative examples of agencies that have initiated mechanisms that promote broad approaches to water management. These provide a status report on several current attempts at solving meta-problems. Each agency relies on the best information available to make informed decisions, and on collaboration with other agencies, governments, stakeholders and the public.

Current Status – Recent Experiences in Managing for Integrated and Cumulative Threats

Management plans for future threats will vary within and amongst jurisdictions, and within each watershed. Watershed planning, groundwater management studies, and impact assessment procedures can help formulate decisions. In Canada, provincial governments have primary responsibility for managing natural resources, including water. The federal government has narrower, but important, responsibilities relating to areas such as fisheries, navigation, federal lands, and transboundary matters. Federal, provincial and municipal governments may collect information on natural resources and provide this information to the public. Water resource agencies may regulate or license water-use activities and charge applicable fees.

Governments at all levels have developed processes to ensure that the public interest is well served; however, no "single" perfect management arrangement exists to address and respond to integrated and cumulative problems. It can be difficult to identify a central management authority for each major watershed that could respond effectively to cumulative threats (e.g., globalization effects, climate change, technological change/risks). Meeting such challenges would require a coordinated response among many parties (e.g., hydro, irrigation, flood control, aquatic ecosystems, fisheries, navigation, municipal/domestic/industry) and jurisdictions.

Examples of integrative approaches to water management reflect the ability of institutional arrangements to address integrated and cumulative threats. We present here an overview of water problems in the Columbia River basin, followed by a description of the integrated approaches applied by the Prairie Provinces Water Board and the Great Lakes Charter.



City of Guelph outside water use program, in "Level 2 Red."

Example of an Integrated and Cumulative Threat – the Columbia River Basin

A case study of the historical development of the Columbia River basin, and the evolving institutional response to various issues in the basin over time, presents a useful illustration of the importance of the evolution of a cumulative threat, and the formidable challenges associated with defining appropriate problem boundaries for planning, impacts assessment, and institutional response. Figure 1 illustrates how the problem boundaries have expanded since the ratification of the Columbia River Treaty (CRT) in 1964. The CRT led to the construction of a reservoir operating system, comprised of several dams in the U.S. and Canada (e.g., Keenleyside, Duncan, Mica, Libby, etc.). The system was oriented toward transboundary aspects of winter dominant hydroelectric production and flood mitigation. Following construction of the four new storage projects authorized by the CRT, and Dworshak Dam[1] (1973) in the U.S., the timing of regulated flow in the Columbia was dramatically altered. Despite far-reaching ecological implications of these changes in flow regime, ecological considerations were not within the institutional problem boundary at the time, and the CRT defined no formal, binational, coordination mechanism for maintaining instream flows for the ecosystem.

The completion of the Libby Dam in 1976 marked the end of the period of major dam construction in the Columbia authorized by the CRT[2], and the beginning of an evolving awareness of, and institutional response to, the impacts of development. Perhaps the most far reaching of these impacts have been those relating to the Columbia's salmon fishery. While commercial fishing, dam blockage, and habitat destruction had created considerable impacts to salmon stocks in the Columbia prior to the CRT, the completion of the CRT dams and poor ocean survival from 1977 to 1995 quickly brought the salmon issue to a crisis level. Institutional response followed. The *Northwest Power Planning and Conservation Act* (1980) in the U.S. established the equality of hydropower and salmon in the Columbia under U.S. law, and the Northwest Power Planning Council was formed in the U.S. to attempt to establish a more equitable relationship between reservoir operations for hydropower and fish. Despite this legislation and a host of ongoing "engineering" solutions to the salmon problem (e.g., increased use of hatcheries and barging of juvenile fish to the ocean to avoid problems in the freshwater habitat), no substantive adjustments were made to the Columbia's reservoir operating policies until *Endangered Species Act* (ESA) listings for several salmon stocks in the late 1980s in the U.S. forced an intervention by the

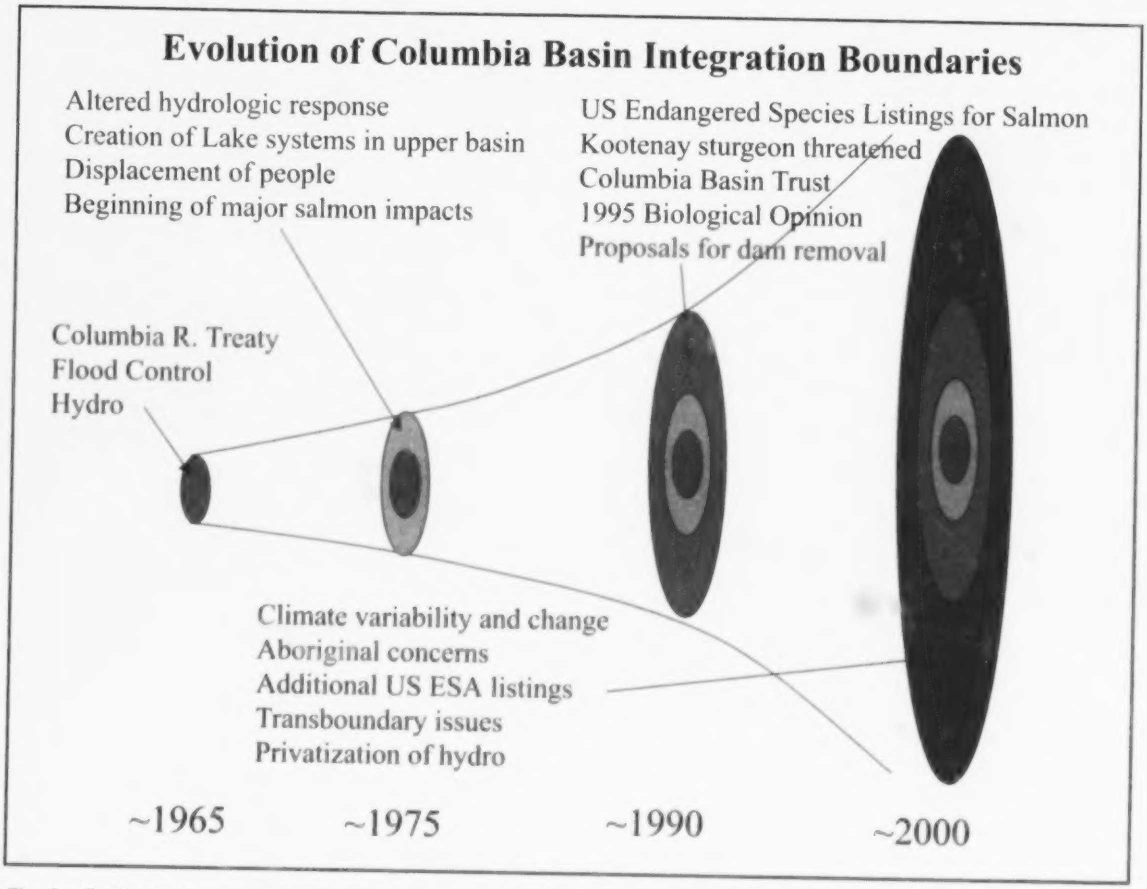

Evolution of Columbia Basin Integration Boundaries
Altered hydrologic response
Creation of Lake systems in upper basin
Displacement of people
Beginning of major salmon impacts
US Endangered Species Listings for Salmon
Kootenay sturgeon threatened
Columbia Basin Trust
1995 Biological Opinion
Proposals for dam removal
Columbia R. Treaty
Flood Control
Hydro
Climate variability and change
Aboriginal concerns
Additional US ESA listings
Transboundary issues
Privatization of hydro
~1965
~1975
~1990
~2000

Fig. 1. Challenge of expanding water management problems: evolution of Columbia basin management issues from 1965 to present.

National Marine Fisheries Service (NMFS), which ultimately resulted in some significant changes in the Columbia's reservoir operating policies in 1995 (National Marine Fisheries Service, 1995) and again in 2000 (National Marine Fisheries Service, 2000).

In the 1990s institutional problem boundaries expanded markedly to include the following:

- protection of additional salmon species in the lower basin, and the Kootenay (Kootenai) River sturgeon listed under the U.S. ESA
- protection and restoration of riparian and instream habitat
- increased monitoring and management for water temperature and gas content
- increased protection of lake ecosystems in the upper basin (in conflict with U.S. instream flow needs)
- compensation for people displaced or affected by dam construction (e.g., The Columbia Basin Trust)
- proposed removal of four large run-of-river dams in the lower Snake River
- impacts of climate variability and climate change
- proposed changes to water law and water allocation practice for irrigation (e.g., water banks and water markets), and
- changes in regional and international energy policy (e.g., deregulated energy markets).

Most of the issues listed above have emerged outside the relatively narrow institutional problem boundaries in place less than a decade ago (Bankes, 1996; Volkman, 1997; O'Neil, 1997; Miller, 2000; Cohen et al., 2000). The result is that managers and policy makers on both sides of the international border are being called upon to manage the Columbia's water resources on a more integrated basis, involving ecological, economic, political, and cultural factors within a relatively narrow framework of institutional arrangements that were never designed to encompass these diverse management concerns.

Example of Integrated Approach: Great Lakes Charter

While the Great Lakes is a large freshwater system, it is a finite system and only a small proportion of the waters are renewed annually. Increasing or new consumptive uses such as irrigation, manufacturing and industrial processes, exports (bulk water transfers and bottled water sales) as well as diversions (into and out of the Great Lakes watershed for navigation, municipal water supply and waste assimilation, hydro generation) may have adverse impacts on the sustainability of water resources in the Great Lakes region. Historically, conflicts and controversies have occurred about use and diversion of water from the Great Lakes, particularly at Chicago where the U.S. Supreme Court intervened on several occasions over matters of water quality, navigation, increasing domestic and industrial demand, and diversion for drought mitigation outside the region. Climate change may exacerbate these (Changnon and Glantz, 1996).

In 1983, the Council of Great Lakes Governors created a task force to develop an institutional framework for dealing with diversions of water from the Great Lakes; this framework led to the 1985 Great Lakes Charter. The Charter builds upon the initial intent to "preserve levels and flows" in the Boundary Waters Treaty of 1909. It also recognizes that Great Lakes waters are interconnected and should be treated as a single hydrologic system transcending basin political boundaries, and that multiple uses of the water resource, maintenance of habitat, and balanced ecosystem are interdependent. Water resources management is guided by five principles: integrity of the Great Lakes basin; cooperation between jurisdictions; protection of Great Lakes water resources; prior notice and consultation; and cooperative programs and practices. While the Charter is considered a "soft law" instrument and is not legally binding on the signatories, through consensus and cooperation it does help guide the behaviour of the eight Great Lakes states and two provinces (Saunders, 2000). Most importantly, any major new or increased diversion or consumptive use of Great Lakes basin water requires prior notification, consultation and concurrence of all affected parties. The Charter states that it is the "intent of the signatory states and provinces that diversions of basin water resources will not be allowed if individually or cumulatively they would have any significant adverse impacts on lake levels, in-basin uses and the Great Lakes ecosystem" (Council of Great Lakes Governors, 1985).

Recognizing that implementation of measures to protect the water resources of the Lakes will fall to the signatories, the Charter states that the eight states and two provinces will implement legislation to establish programs to manage and regulate diversions and consumptive uses. Ontario is an example of a jurisdiction that has addressed this commitment. The *Ontario Water Taking and Transfer Regulation* (Ontario Regulation 285/99), made under the *Ontario Water Resources Act* (Revised Statutes of Ontario 1990, Chapter O.40), requires that decisions made regarding water allocation through Permits to Take Water "shall ensure that Ontario's obligations under the Great Lakes Charter with respect to the application are complied with (Ontario Regulation 285/99, Section 4)."

A potential application of the Great Lakes Charter may arise in the context of the proposed pipeline from the Great Lakes to the Regional Municipality of Waterloo (RMOW). Pressure on sub-regional water resources (the Grand River basin) comes from urban growth. This has tested the limits of the available supply for several decades. The RMOW, currently 80% groundwater dependent, is planning for a pipeline to one of the Great Lakes by 2035. Low water levels due to recent droughts in 1997 to 1999 and 2001 to 2002 have necessitated water-use restrictions in urban areas, and have created conflicts in areas of heavy irrigation. Threats to water quality originate from agricultural activities, treated wastewater discharges, and industrial and commercial activities (Grand River Conservation Authority, 1998). Wellhead and aquifer protection planning at the local level have emerged as a priority for the Grand River, with the RMOW playing a leading role due to its early experience with contamination of the water supply of the Village of Elmira from N-nitrosodimethylamine in 1989 (Neufeld, 2000). If one is developed, and depending on which lake is the source, this project could be viewed as an interbasin transfer and undermine the intent of the Boundary Waters Treaty – to preserve levels and flows. If other communities within and adjacent to the basin had similar proposals, the cumulative effects on some economic, social and ecological activities could be significant.

In 2001, a Supplementary Agreement to the Great Lakes Charter was signed. It reiterates the commitments under the Charter but commits the Great Lakes states and provinces to prepare a basin-wide binding agreement, establish a decision-making standard for review of proposals, develop public participation, and identify decision-making and dispute-resolution mechanisms (Council of Great Lakes Governors, 2001). This mechanism might anticipate the potential problems with interbasin transfers and provide for an effective and equitable allocation of water resources between instream and withdrawal users. Developing mechanisms and procedures that effectively balance basin-wide interests and needs with regional and local ones is an emerging theme related to cumulative and integrated threats.

The Charter is an innovative example of trans-national cooperation, yet problems exist at the sub-national level (Saunders, 2000). To implement the Charter, signatories agreed to collect common water use and management data, facilitate data exchange, establish a Water Resources Management Committee, develop a Great Lakes Basin Water Resources Management Program, and coordinate research. Some aspects are not fully implemented (International Joint Commission, 2000). Deficiencies in the water use data make accurate accounting difficult. The trigger level for notification of water diversion or consumptive use projects (greater than 19 million litres per day over a 30-day period) is high; smaller projects can have cumulative impacts but are not addressed. While affected parties must be notified and consulted on diversions, they lack a veto for projects.

Example of an Integrated Approach: Prairie Provinces Water Board

Runoff from the eastern slopes of the Rocky Mountains is the major source for the larger southern rivers of the Prairie Provinces. These larger rivers flow eastward across Alberta, Saskatchewan and Manitoba to empty into the Hudson Bay. Some streams originate off the Prairies and from heights of land, such as the Cypress Hills. These streams may also flow east across provincial boundaries before joining the larger rivers or forming landlocked lakes. Ownership of the waters of a river system flowing through two or more jurisdictions can give rise to many administrative and water-use problems.

In 1948, Manitoba, Saskatchewan, Alberta and Canada agreed to establish the Prairie Provinces Water Board (PPWB) to recommend the best use of interprovincial waters in relation to associated resources in Manitoba, Saskatchewan and Alberta, and to recommend allocation of water between each province for streams flowing from one province into another.

In 1969, the four governments entered into the Master Agreement on Apportionment to provide an apportionment formula for eastward flowing interprovincial streams, to recognize the problem of water quality, and to reconstitute the PPWB to administer the Agreement. The Master Agreement was amended in 1984 to clarify apportionment arrangements for the Battle, Lodge and Middle creeks, which are international as well as interprovincial streams: in 1992 to add a Water Quality Agreement, and in 1999 to define interprovincial lakes as water courses under the Agreement.

The Master Agreement is based on the principle of equitable sharing of available water in the Prairies. The formula generally states that each province may use one half of the natural flow of water originating within its boundaries and one half of any flow entering the province. Natural flow is broadly defined as the volume of flow that would occur if a river had not been affected by human activity. The Agreement also allows comparing water quality at interprovincial boundaries to acceptable levels, and facilitates a cooperative approach for the integrated development and management of interprovincial streams and aquifers to ensure their sustainability for the benefit of the people of the Prairie Provinces.

The PPWB Secretariat performs the day-to-day work of the Board, with its office in Regina. The Secretariat, made up of Environment Canada staff, reviews and analyzes monitoring data, calculates natural flow at the boundaries, determines conformity with water quality objectives, and reports on apportionment and water quality at the interprovincial boundaries. The PPWB has three permanent committees on water quantity, water quality and groundwater to assist in technical work and to provide advice to the Board.

Environment Canada fulfills the monitoring conditions described under the Master Agreement and provides information from 75 long-term water quantity monitoring stations, 16 meteorological stations and 12 water quality monitoring sites. Other agencies provide information from an additional 13 water quantity monitoring stations. This information is used to calculate natural flows and levels of water quality parameters.

The values calculated for 14 water quantity and 12 water quality monitoring sites along the Alberta-Saskatchewan and Saskatchewan-Manitoba borders are used by the PPWB to decide whether or not requirements of the Agreement are being met. Although the Agreement applies to all eastward flowing interprovincial streams, formal apportionment calculations are only done for streams with significant water use.

Since being signed, the Master Agreement on Apportionment has allowed the equitable sharing and protection of interprovincial streams while developing a consensus approach to preventing interprovincial surface and ground water problems. The PPWB has always sought a consensus of its members, so provincial governments, the primary regulator of water supplies, have always complied with the Agreement. Therefore, the Master Agreement could be considered a model for dealing with interjurisdictional issues.

Trends in Management, Planning and Research

From an initial reliance exclusively on supply management (e.g., reservoir expansion), the recent trend in areas with tight supplies appears to have an increasing emphasis on demand management options (e.g., metering, pricing, information campaigns). Regarding water allocation, the focus had been more on withdrawals than instream issues, and instream concerns in managed waterways focussed on navigation, recreation and dilution of pollutants. In natural rivers, instream flow (in allocation criteria) has often been defined by probability of minimum flow (Pearce et al., 1985). This definition is now changing toward a broader concept that incorporates ecosystem requirements, as illustrated in the South Saskatchewan River case discussed below.

Research priorities and changes in institutional arrangements have frequently been related to changes in the resource itself, such as immediate threats of inadequate supply, conflicts among users, and threats to human health (e.g., contamination of the municipal water supply

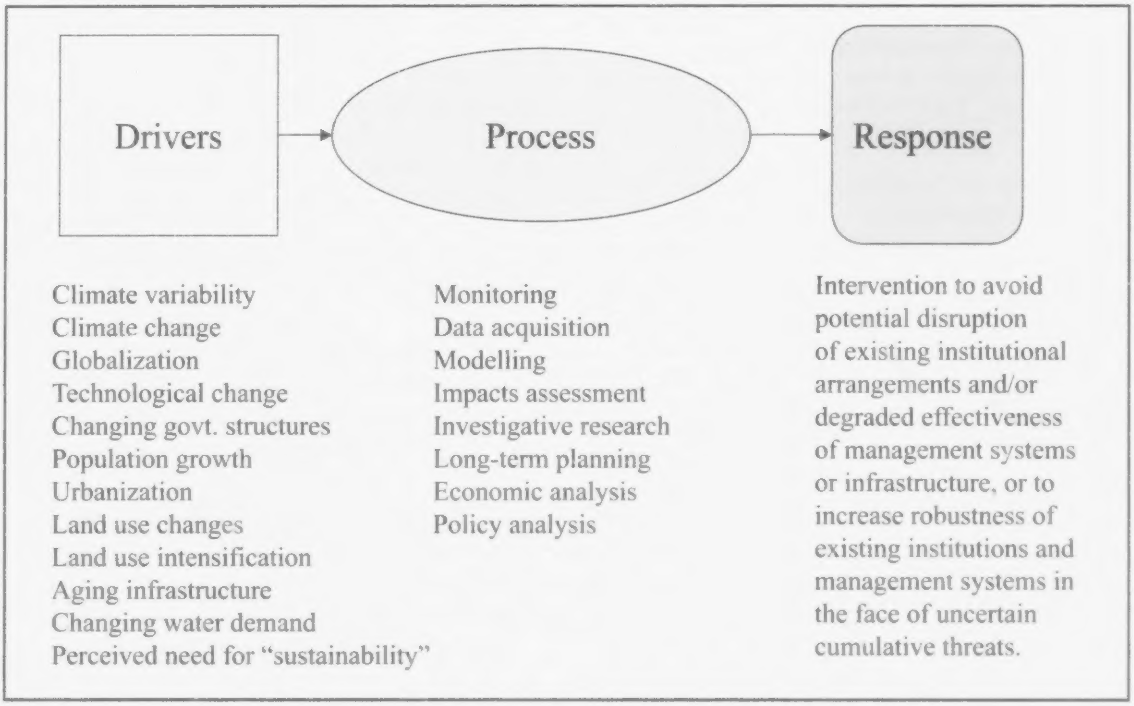

Drivers
Process
Response
Climate variability
Climate change
Globalization
Technological change
Changing govt. structures
Population growth
Urbanization
Land use changes
Land use intensification
Aging infrastructure
Changing water demand
Perceived need for "sustainability"
Monitoring
Data acquisition
Modelling
Impacts assessment
Investigative research
Long-term planning
Economic analysis
Policy analysis
Intervention to avoid potential disruption of existing institutional arrangements and/or degraded effectiveness of management systems or infrastructure, or to increase robustness of existing institutions and management systems in the face of uncertain cumulative threats.

Fig. 2. Framework for evaluating and responding to cumulative threats to water supply.

in Walkerton, Ontario, in 2000). A broad list of emerging drivers includes external forces, such as climate change, globalization, perceived need for sustainability, etc., and domestic forces, such as land-use change, land-use intensification, changing government structures, and ageing infrastructure (Fig. 2). The process evolving to address challenges posed by various drivers includes institutional change and new consultation and assessment procedures.

Potential impacts of climate change on water resources systems have presented special challenges to the water management community because the impacts are uncertain, cumulative in nature, and will probably evolve over a very long time horizon. Ongoing efforts to find appropriate institutional responses to the potential impacts of climate change may serve as an illustration of the challenges involved in attempting to include integrated effects of uncertain cumulative drivers in long-range planning. In the research community, climate change research is moving beyond sensitivity studies based on assessments of hydrologic impacts to include increased emphasis on integrated assessment, incorporating institutional and socio-economic considerations (e.g., Okanagan/Columbia – Cohen et al., 2000; Miles et al., 2000; Hamlet, 2003; Cohen and Neale, 2003). Dialogue on cumulative issues such as climate change is also increasingly evident in professional and umbrella organizations, including the Canadian Water Resources Association, American Water Resources Association, British Columbia Water Supply Association, the Federation of Canadian Municipalities, and within regional watershed groups (e.g., Fraser Basin Council). In the U.S., a few recent planning exercises in the Pacific Northwest (e.g., Palmer and Hahn, 2003) and in California (State Water Plan, Bulletin 160-03) have begun the process of integrating climate change scenarios with more traditional elements of long-term planning. Experience gained in these first attempts may help to provide a road map for similar studies in other areas of the U.S. and in Canada.

Example of Broader Management: South Saskatchewan River Basin Water Management Plan – Alberta

The South Saskatchewan River comprises part of the Saskatchewan River basin. As noted earlier, water apportionment among the Prairie Provinces is guided by the Prairie Provinces Water Board. Water allocation within the Province of Alberta is the responsibility of Alberta Environment, and is guided by the doctrine of prior appropriation. Water rights were traditionally assigned to users with limited consideration for instream water uses. This shortcoming has been addressed in an incremental manner over the last 25 years in response to an increased awareness to maintain instream flows, increased competition among water users, and recent periods of low water flows. At that time, the government introduced, among other measures, water trading.

In response to continued demands on the water resources of the South Saskatchewan River basin (SSRB), Alberta is developing a SSRB Water Management Plan. Phase I of the SSRB Water Management Plan, completed in June 2002 (Alberta Environment, 2002), has the following attributes:

- authorizes a designated "Director" to consider applications for water allocation transfers and to use water conservation holdbacks
- provides guidance to the Director on matters to be considered when reviewing an application for a water allocation transfer
- provides information to the Director on water conservation holdbacks, and an interim closure of the Oldman River's southern tributaries to new allocations, and
- commits Alberta Environment to a number of actions, including an additional phase of water management planning for the establishment of water conservation objectives.

The second phase of the Water Management Plan will focus on determining requirements for human needs and the needs of the aquatic environment. The key goal of the second phase will be to reach compromises between these competing interests and make wise choices. The second phase is scheduled for completion in early 2004.

Alberta is also undertaking a Southern Alberta Regional Strategy that will develop a vision of the future for southern Alberta and the desired environmental, social, and economic benefits for the region. Alberta then will address the issues and follow a plan to achieve the vision. The first phase, *Defining the Agenda*, will appraise the current state of the region, identify a vision, goals, and principles for sustainable development, make policy recommendations and identify key issues to be addressed, and in what order of priority. Phase 1 will compile air, water, land-use and socio-economic data, build landscape modelling and simulation tools, and gather information about important resource sectors. Phase 1 should be completed before the summer of 2003.

Lessons

Recent experiences with water meta-problems can be summarized as follows:

- cumulative threats to watersheds can result from fragmented decision making
- there are good examples of integrated management approaches for a number of Canadian watersheds, and
- research and dialogue are expanding, but there is a need to broaden the range of tools available, including those that support demand-side management, and to apply these throughout Canada.

Knowledge and Program Needs

A general framework for generating policy and management responses to integrated and cumulative threats is shown in Fig. 2. The process includes a wide range of technical, economic and social analyses. Measures of performance for management activities may include ecosystem health, human health, economic measures, long-term sustainability, and whether expectations of stakeholders have been met.

The focus of this chapter is on management aspects of addressing integrated and cumulative threats. One overarching question is whether this framework is able to address future challenges (e.g., population growth, globalization impacts on regional development, climate change, etc.) that water systems and institutions may be unable to plan for. Management issues have been generated as a result of human demands to use water resources. In response, governments have developed institutional arrangements to promote further economic development by providing secure water supplies or to allocate water among users (municipal, industrial and rural uses, navigation, electric power production, and low flow augmentation). However, if a change in operating conditions occurs (e.g., due to new facilities, climate change, etc.), and reservoir rule curves or allocation systems no longer work as they were originally intended, a lengthy decision-making process would be needed to make changes. Examples include the IJC levels order for Kootenay Lake within the Columbia system (Bankes, 1996), and regulation plans for lakes Superior and Ontario (Sousounis and Bisanz, 2000; Mortsch et al., 2000).

New Questions?

Questions arising from this chapter include:

- how sustainable are Canada's groundwater and surface water resources in the context of the past 250 years of climate variability and potential changes in climate expected in the next 100 years? How do we measure sustainability? Are the uncertainties so large that we cannot answer the question in any meaningful way? If so, what then?
- how (and on what basis – e.g., economic, social considerations) can water best be allocated between competing uses and users of water?
- how should instream flow requirements be determined and managed (tradeoffs between ecological considerations and human needs)?
- how can more flexible water management institutions be developed that can respond to changing conditions without recursive policy intervention as unanticipated problems emerge?
- how can issues of governance be addressed in water management to ensure that institutional fragmenta-

tion does not dominate response capability to changing conditions?

- what role can technological innovations play in coping with increasing demand and limited supplies? Where will different technologies find their best application and at what cost?, and
- what formal linkages between water resources planning and land-use planning are needed to ensure sustainability?

Recommendations

In conclusion, our main recommendations for addressing integrated and cumulative threats to water availability in Canada are that government and non-government water interests should:

1. Assess integrated and cumulative threats and create appropriate linkages to water planning and management

At the broadest level, there is a need to identify and assess more fully the integrated and cumulative threats deriving from all the individual threats identified in other chapters of this book, and to use this information effectively in water resources planning and management at the river basin, provincial, national, and international levels of governance.

2. Make dialogue an explicit tool of management

Water resources managers and planners frequently involve, collaborate and partner with stakeholders for a variety of reasons. Given the expanding complexity of water meta-problems, regular dialogue with stakeholders provides opportunities to expand the knowledge base beyond discussions on the physical attributes of a water system. This will facilitate a broader framing of the problems at hand. The challenge is to create processes that can assess and possibly improve the capacity of government and non-government bodies to manage effectively for cumulative threats. This includes: (i) identifying various forms of partnerships and their relative strengths and weaknesses; (ii) assessing the capacity of government and non-government partners to enter into partnerships; (iii) determining factors that support effective partnerships; and (iv) ensuring that appropriate levels of accountability, effectiveness, efficiency, and equity are maintained in the management of water quantity.

At a program level, there is a need to clearly define the role of governments in building capacity among relevant non-government partners, and to provide training in group processes and conflict resolution strategies to improve the effectiveness of institutional arrangements and interactions with stakeholders.

3. Utilize a broader range of policy instruments

A broad range of choice to solve problems has been one indicator of effective water management; however, programs have often become dominated by one approach, as illustrated in the construction of reservoirs in the Columbia River. There are a range of well-known options that can support demand-side management, including information campaigns, subsidies for applying new technology (e.g., drip irrigation), regulation, and pricing structures for public and private delivery of services.

On a practical level, program needs involve ensuring that financing projects does not bias one approach over effective alternative solutions; and that the direct and indirect impacts of implementation are carefully considered. In the absence of the latter, unintended consequences will have to be "fixed" continually, as evidenced in the Columbia basin.

4. Give consideration to equity and sustainability in decision making

Traditional measures of effectiveness and efficiency that have dominated the establishment of program goals and program evaluation frequently have a relatively short time horizon. The concept of sustainable development challenges us to broaden these criteria to embrace measures of meeting intergenerational needs. In the absence of further technological developments that might decrease water demand or provide alternative supplies, increased demands on water resources also promote the need to devote more attention to fair treatment of water users in both the decision-making process and the final decisions concerning water allocation. This aspect is highlighted by the treatment of aboriginal communities in Canada who may resort to the legal system to assert their rights to adequate water supplies. For example, Rush (2002) described a claim to a water right made by the Piikani Nation under Treaty 7 to the water of the Oldman River flowing through the reserve in southern Alberta. Although no Canadian Court has decided a case involving a claim to water rights, Rush (2002) maintained that the case law developed to date in Canada in relation to land might support the existence of aboriginal rights to water. In 2002, a negotiated settlement between the Alberta Government and the Piikani included the following:

- payment of $64.3 million in settlement funds to be paid into trust
- annual pay-out of $800,000 (indexed to inflation)
- estimated $125 million in revenues over next 50 years generated on the trust
- $3000 per capita distribution to Piikani members
- Lethbridge Northern Irrigation District (LNID) canal lands to be transferred to Alberta
- assured water supply from the instream of the Oldman River to meet residential, community, and agricultural needs; and allocation of 37,000 acre feet of water under Alberta Water legislation for the Band's commercial needs

- participation in the Oldman River Dam Hydro Project
- settlement of nine specific claims against Canada (for $32.17 million)
- discontinuance of water rights litigation by Piikani
- discontinuance of claims in respect of LNID headworks
- Piikani agreement not to bring forward any other litigation for so long as Alberta needs the LNID headworks for diversion of water from Oldman river, and
- no prior or superior entitlement to water.

Aboriginal communities who wish to seek the support of the courts in ensuring their water rights might file similar legal suits in the future.

5. Increase the capacity of institutions to respond

Capacity building has been defined as increasing the ability of people and institutions to do what is expected and required of them. Over the past 10 to 15 years, the roles, expectations and requirements of government and non-government participants and the public in water management have changed. Capacity is based on several sectoral factors, including access to technical resources (data, skill, staff); availability of financial resources; quality of institutional arrangements; extent to which citizens are involved in decision making; and leadership (de Loë et al., 2002). These various dimensions of capacity are closely interrelated. As responsibilities shift among the various parties involved in water management, and as new challenges emerge, attention should be directed to the capacity of organizations and communities. Capacity building is thus emerging as an important feature of water management.

To complement ongoing research on the hydrologic cycle itself, or on improving supply and demand planning and management, future research should consider the drivers that influence the resource as well as the region's management capabilities. In addition, since many watersheds in Canada cross provincial and international borders, Canada, in collaboration with regional partners and the International Joint Commission, should systematically review various models of inter-jurisdictional water management.

6. Increase the investment in databases and improve access to data

Canada, in collaboration with regional partners, has invested in a long-term water quantity monitoring system. Some short-term information is also available for water demand and water chemistry. Little information is available on aquatic and riparian biology.

Since the major users of water information may not collect the data, access to information collected at public expense is a major issue. But it is not an easy task to create and maintain detailed databases. Investment in database infrastructure will require a range of stakeholders. The water management community as a whole (stakeholders, managers, administrators, policy makers) should consider how best to create such partnerships. The evaluation of integrated and cumulative threats to water availability may require many different kinds of data from a wide variety of sources.

7. Broaden the research effort

A review of water resources research was completed as part of the 1985 Inquiry into Federal Water Policy (Pearce et al., 1985). Among its many findings, it suggested the following:

- Canada had a record of providing only modest support for water research of most kinds
- water quality research had received the majority of federal funding, and much of it focussed on Ontario and Quebec
- groundwater and efficiency of water use were two topics requiring further study, and
- much of the research was oriented towards engineering and natural science relative to the social sciences.

Research developments since that time have been mixed. On the one hand, the NSERC Canada Research Chair program and the Networks for Centres of Excellence have promoted water-oriented research at universities. What is less clear is to what extent these and other initiatives address water quantity concerns, especially from social science perspectives. The capacity of governments to undertake research has diminished as a result of cutbacks in the 1990s. The state of water resources research in Canada should be revisited to determine what, if any, progress has been made since the 1985 Federal Water Inquiry, and to identify future opportunities.

We have not attempted to rank these in order of importance. We hope that as these recommendations are considered, a consensus can be reached on how they may be implemented in watersheds throughout Canada.

Acknowledgements

The authors would like to thank external reviewer Peter Gleick, and internal reviewers for their constructive assessment of this chapter.

References

Alberta Environment. 2002. South Saskatchewan River basin water management plan, phase one: water allocation transfers. Department of Environment, Government of Alberta, Calgary, Alberta, June 2002.

Bankes, N. 1996. The Columbia basin and the Columbia River Treaty: Canadian perspectives in the 1990s. Faculty of Law, University of Calgary, submitted to Northwest Water Law and Policy Project.

Changnon, S. and M. Glantz. 1996. The Great Lakes diversion at Chicago and its implications for climate change. Climatic Change 32: 199-214.

Cohen, S.J., K.A. Miller, A.F. Hamlet and W. Avis. 2000. Climate change and resource management in the Columbia River Basin. Water International 25(2): 253-272.

Cohen, S. and T. Neale (ed.). 2003. Expanding the dialogue on climate change and water management in the Okanagan Basin, British Columbia. Interim Report, Project A463/433, submitted to Climate Change Action Fund, Natural Resources Canada, Ottawa. 150 p.

Council of Great Lakes Governors. 1985. The Great Lakes Charter. Principles for the Management of Great Lakes Water Resources. Available at: http://www.cglg.org/pub/charter/index.html; Internet. Cited 10 October 2003.

Council of Great Lakes Governors. 2001. The Great Lakes Charter Annex. A supplementary agreement to the Great Lakes Charter, June 18, 2001. 4 p.

de Loë, R.C., S. Di Giantomasso and R.D. Kreutzwiser. 2002. Local capacity for groundwater protection in Ontario. Environmental Management 29(2): 217-233.

Grand River Conservation Authority. 1998. State of the Grand River Watershed: focus on watershed issues, 1996-1997. GRCA, Cambridge, Ontario.

Hamlet, A.F. 2003. The role of transboundary agreements in the Columbia River basin: an integrated assessment in the context of historic development, climate, and evolving water policy. *In* Diaz, H. and B. Morehouse (ed.), Transboundary challenges in the Americas. Kluwer Press, Dordrecht.

International Joint Commission (IJC). 2000. Protection of the waters of the Great Lakes. Final Report to the Governments of Canada and the United States, February.

Miles, E.L., A.K. Snover, A. Hamlet, B. Callahan and D. Fluharty. 2000. Pacific Northwest regional assessment: the impacts of climate variability and climate change on the water resources of the Columbia River basin. Journal of the American Water Resources Association 36(2): 399-420.

Miller, K.A. 2000. Managing supply variability: the use of water banks in the Western U.S., p. 70-86. *In* Wilhite, D.A. (ed.), Drought: a global assessment, Vol. II. Routledge, London.

Mitchell, B. 2002. Resource and environmental management, 2nd edition. Prentice Hall, London.

Mortsch, L., H. Hengeveld, M. Lister, B. Lofgren, F. Quinn, M. Slivitzky and L. Wenger. 2000. Climate change impacts on the hydrology of the Great Lakes-St. Lawrence system. Canadian Water Resources Journal 25(2): 153-179.

National Marine Fisheries Service. 1995. Biological opinion: reinitiation of consultation on 1994-1998 operation of the Federal Columbia River power system and juvenile transportation program in 1995 and future years, Section 7 *Endangered Species Act* Consultation.

National Marine Fisheries Service. 2000. Biological opinion: reinitiation of consultation on operation of the federal Columbia River Power System, including the juvenile fish transportation program, and 19 Bureau of Reclamation Projects in the Columbia Basin, Section 7 *Endangered Species Act* Consultation, December.

Neufeld, D.A. 2000. An ecosystem approach to planning for groundwater: the case of Waterloo Region, Ontario, Canada. Hydrogeology Journal 8: 239-250.

O'Neil, P. 1997. B.C. compensation for power rejected. Vancouver Sun, October 23.

Palmer, R.N. and M. Hahn. 2003. The impacts of climate change on Portland's water supply: an investigation of potential hydrologic and management impacts on the Bull Run system. Report prepared for the Portland Water Bureau, University of Washington, Seattle. 67 p.

Pearce, P., F. Bertrand and J.W. MacLaren. 1985. Currents of change: final report of the inquiry on federal water policy. Environment Canada, Ottawa.

Rush, S. 2002. Aboriginal water rights in Canada. Presented to the Just Add Water 2002 Conference, Saskatoon, Saskatchewan, October 3-4, 2002.

Saunders, J.O. 2000. Law and the management of the Great Lakes. Canadian Water Resources Journal 25(2): 209-242.

Sousinis, P.J. and J.M. Bisanz (ed.). 2000. Preparing for a changing climate: the potential consequences of climate variability and change – Great Lakes overview. A report of the Great Lakes Regional Assessment Group for the U.S. Global Change Research Program.

Volkman, J.M. 1997. A river in common: the Columbia River, the salmon ecosystem and water policy. Report to the Western Water Policy Review Advisory Commission.

Additional Sources

DeVillers, M. 2000. Water. Houghton Mifflin Company, Boston.

Ellis, J. 1996. Drafting from an overdrawn account: continuing water diversions from the mainstem Columbia and Snake Rivers. Environmental Law 26: 299-322.

Foster, H.D. and W.R.D. Sewell. 1981. Water: the emerging crisis in Canada. James Lorimer & Company, Toronto.

Gleick, P. 1998. The world's water. The biennial report on freshwater resources 1998-1999. Island Press, Washington.

Gleick, P. 2000. The world's water. The biennial report on freshwater resources 2000-2001. Island Press, Washington.

Gleick, P. with W.C.G. Burns, E.L. Chalecki, M. Cohen, K.K. Cushing, A.S. Mann, R. Reyes, G.H. Wolff and A.K. Wong. 2002. The world's water. The biennial report on freshwater resources 2002-2003. Island Press, Washington.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate change 2001: impacts adaptation and vulnerability. Cambridge University Press, Cambridge. Available at: http://www.ipcc.ch; Internet. Cited 10 October 2003.

Mitchell, B. 1990. Integrated water management: international experiences and perspectives. Belhaven, New York.

Mitchell, B. and J.S. Gardiner (ed.). 1983. River basin management; Canadian experiences. University of Waterloo Department of Geography Publication Series No. 35.

Mitchell, B. and D. Shrubsole. 1994. Canadian water management: visions for sustainability. Canadian Water Resources Association, Cambridge, Ontario.

Mitchell, B. and D. Shrubsole. 1992. Ontario conservation authorities: myth and reality. University of Waterloo Department of Geography Publication Series No. 35.

Shrubsole, D. 1992. Integrated water management strategies in Canada, p. 88-118. *In* Mitchell, B. (ed.), Integrated water management: international experiences and perspectives. Belhaven, New York.

Shrubsole, D. and B. Mitchell (ed.). 1997. Practising sustainable water management: Canadian and international experiences. Canadian Water Resources Association, Cambridge, Ontario.

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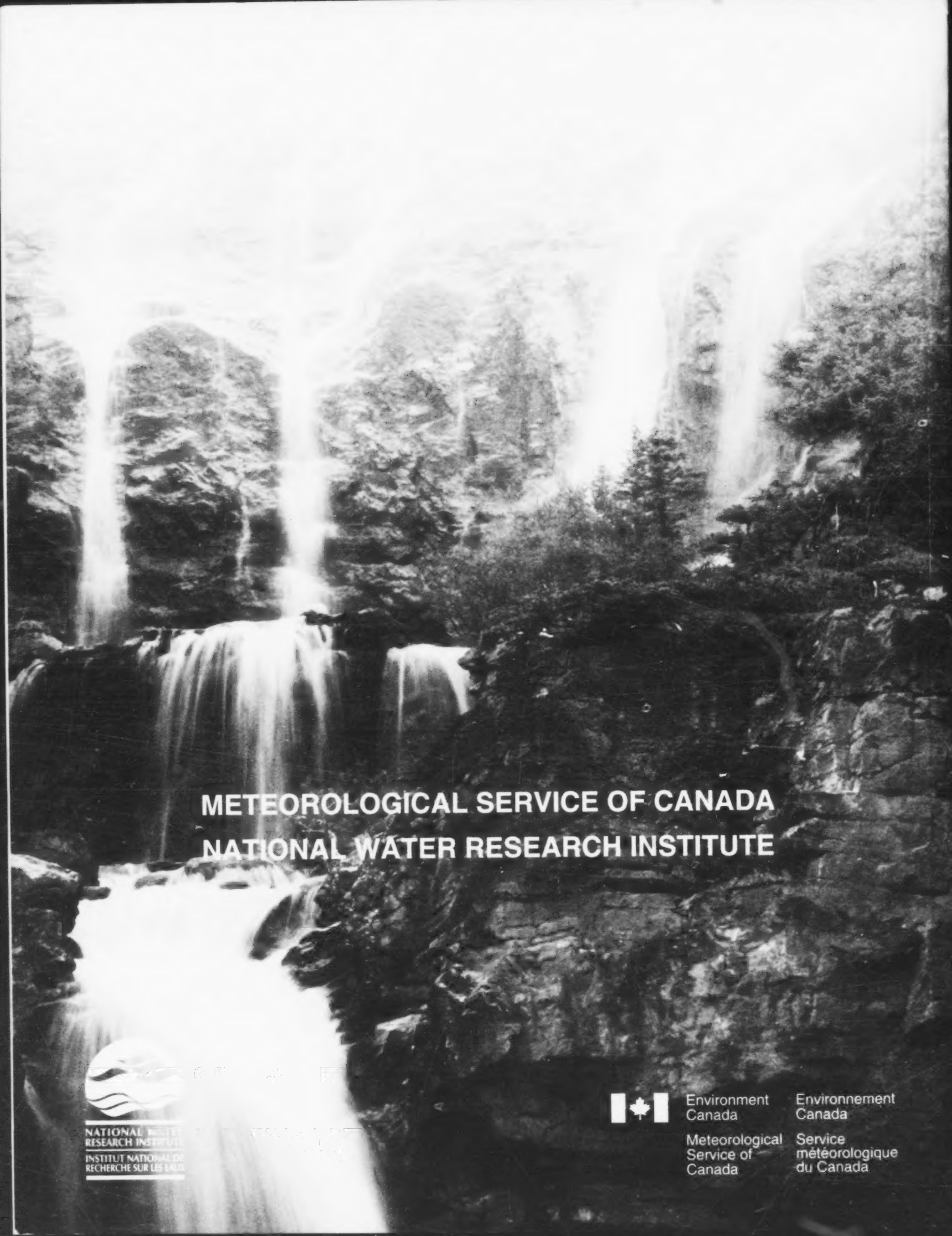
[1] Although Dworshak Dam was completed before Libby Dam, Dworshak's construction was not directly associated with the CRT.

[2] Several non-CRT dams were constructed later. BC Hydro constructed Revelstoke Dam as a run-of-river facility below the Mica Dam in 1984 (Bankes, 1996). In the Okanagan, the U.S. built the Zosel Dam in 1987, just south of Osoyoos Lake.



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